Chapter 3
Biostratigraphy

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The Tournaisian and Visean platform carbonate successions of the UK and Ireland initially relied upon development of coral and brachiopod zonations to aid correlation. However, such zones are strongly facies-controlled and are only of local to regional significance. Over recent years, emphasis has been placed upon the use of foraminifers, and notably conodonts, to define international stages. They have been studied increasingly within the Tournaisian and Visean successions of the UK and Ireland, but are of limited stratigraphical value in younger Carboniferous strata. Ammonoids (goniatites) provide the greatest biostratigraphical resolution for the late Visean, Namurian and early Westphalian Stages. Some ammonoid biozones can be recognised across Western Europe and some biozones are applicable globally. However, the marine bands that contain these ammonoids may be absent towards basin margins and marine influence is lost entirely throughout late Westphalian and Stephanian times. Within strata lacking ammonoids, biostratigraphical correlation initially relied upon recognition of non-marine bivalve zonation, but over recent decades palynomorphs (miospores) and plant macrofloras have assumed greater importance.

Ammonoids

Thick-shelled ammonoids provide the greatest biostratigraphical resolution within upper Visean, Namurian and lower Westphalian marine-influenced successions, with the bases of the Brigantian to Langsettian substages defined at ammonoid biozonal boundaries. Ammonoids occur within thin hemipelagic 'marine bands', many of which can be correlated widely across Britain and Ireland. Ammonoid biozones are defined by the successive first appearance of ammonoid taxa, with the base of the biozones coinciding with the bases of specific marine bands (Fig. 3.1).

The Tournaisian ammonoid faunas are mainly recorded in the Munster Basin of southern Ireland (see Chapter 23) and Culm Basin of SW England (see Chapter 4). The base of the *Gattendorfia subinvoluta* Zone equates with the base of the Tournaisian Stage. The Tournaisian and Visean biozonation in Britain is summarised by Riley (1991), and the ranges of late Asbian and Brigantian ammonoids are recorded by Riley (1993). In Scotland, ammonoids are rare and only make a significant appearance during late Visean time.

Ammonoid evolution rates reached an acme during the Namurian, typically with each marine band comprising a distinct ammonoid fauna. The Namurian ammonoid biostratigraphy was developed by Bisat (1924; 1928) and Bisat & Hudson (1943), and later refined by Ramsbottom (1969; 1971); the scheme shown in Fig. 3.1 is derived from Riley *et al*. (1995). Much of the classification resulted from studies within the Central Pennine Basin of northern England, where there are about 60 marine bands in the Namurian. In Scotland and northern England ammonoid-bearing marine shales are comparatively rare.

Key ammonoid-bearing marine bands have also been used as marker beds to divide the thick, cyclical Westphalian Coal Measures lithofacies into chronostratigraphical

and lithostratigraphical units, or to allow correlation of disparate successions. The key marine bands, identified by Ramsbottom *et al*. (1978), are named after the diagnostic ammonoid species, replacing local geographical names. During the Westphalian, the number of marine bands broadly decreases in abundance upwards, with none recorded in Britain and Ireland above the Cambriense Marine Band of Bolsovian age. Correlation in the Westphalian is enhanced by the presence of an additional framework of marker marine bands that contain less diagnostic fauna, such as thin-shelled ammonoids (*Anthracoceras*), marine bivalves (*Dunbarella*), brachiopods (*Lingula*) and crustacea (ostracodes, *Estheria*).

Foraminifers

Carboniferous foraminifers were benthic, living in mainly shallow tropical-subtropical shelves. Hence, in Great Britain and Ireland foraminifers are of biostratigraphical importance within Tournaisian and Visean carbonates, being particularly abundant in mid-ramp and platform settings, but also present within basinal deposits in limestone turbidites (Riley 1993). The formal foraminifer zonation for Belgium Cf1–Cf7 (Fig. 3.2), established as the standard for northwest Europe, has been applied to British and Irish sequences by Conil *et al*. (1980; 1990) and Jones & Somerville (1996). The stratigraphical distribution of British Tournaisian and Visean foraminifers was reported by Fewtrell *et al*. (1981), who also recognised problems with the Chadian and Asbian stratotypes of George *et al*. (1976) and indicated discrepancies with the Belgian zonation scheme. A recent refinement of the Conil et al. foraminiferal zonation for the Mississippian in Belgium (MFZ1-MFZ16) has been proposed by Poty *et al.* (2006) which incorporates all of the zones and subzones of the former zonal scheme for the Tournaisian to Serpukhovian interval.

The boundary between the former Hastarian and Ivorian stages of the Tournaisian corresponded with the boundary between *Chernyshinella* (Cf1) and *Paraendothyra* (*Tournayella)* biozones (Cf2) (Ramsbottom & Mitchell 1980). In Britain and Ireland the Cf2 Biozone is marked by the appearance of *Eblanaia michoti, Eoforschia* sp. *Paraendothyra* sp., *Tournayella discoidea,* and *Tuberendothyra* sp. (Marchant in Charsley 1983; Strogen *et al*. 1990; Jones & Somerville 1996). The late Tournaisian in Ireland (Cf3 Biozone) is dominated by *Tetrataxis, Pseudotaxis* and *Eotextularia diversa.* The latest Tournaisian (Cf4α1 Subzone) in Britain and Ireland contains *Brunsia, Dainella, Latiendothyranopsis, Mediocris, Omphalotis, Plectogyranopsis, Pseudoammodiscus, Pseudolituotuba,* and *Valvulinella* (Strogen *et al*. 1990; Riley 1994; Jones & Somerville 1996).

The succeeding *Eoparastaffella* (Cf4) Zone has been divided into 4 subzones (Cf4α-δ) of which the lowest subzone is further subdivided into Cf4α1 and Cf4α2. The latter is marked by the first appearance of *Eoparastaffella simplex*. It is proposed here to redefine the base of the Chadian Substage to equate with the base of the global Visean Stage, as originally proposed, taken at the first lithological change above the incoming of *Eoparastaffella simplex* (Devuyst *et al*. 2003)*.* The base of the Arundian Substage (former stage) is defined by the first change in lithology below the entry of the family Archaediscidae (George *et al*. 1976). Foraminiferal taxa recorded in Cf4β-δ subzones include *Uralodiscus, Glomodiscus, Planoarchaediscus, Viseidiscus, Nodosarchaediscus* and *Paraarchaediscus* at *involutus* stage, together with *Bogushella* (Conil *et al*. 1980; Somerville & Strank 1984a; Strogen *et al*. 1990).

The succeeding *Koskinotextularia-Pojarkovella nibelis* (Cf5) Zone is defined by the first appearance of both these taxa marking the base of the Holkerian Substage. The zone is also characterised by the first appearance of *Paraarchaediscus* at *concavus* stage, *Holkeria, Nevillea, Palaeotextularia* (monolaminar), *Lituotubella* and *Pseudoendothyra* (Conil *et al.* 1980; Fewtrell *et al.* 1981; Somerville & Strank 1984a).

The overlying *Neoarchaediscus* (Cf6) Zone has been divided into four subzones (Cf6α-δ) (Conil *et al.* 1980; 1991); Cf6α-β equating with the early Asbian, Cf6γ the late Asbian and Cf6δ the Brigantian (Jones & Somerville 1996). Riley (1993) indicated the need to revise the *Neoarchaediscus* (Cf6) Zone, which lacks the eponymous taxon from the lower part of the zone. Moreover, the Cf6β Subzone has not been recognised in Britain and there is uncertainty in its definition (Riley 1993). Cf6α–β subzones are defined by the appearance of *Paraarchaediscus* at *angulatus* stage and *Vissariotaxis* (although rare). The Cf6γ Subzone (late Asbian) is marked by rich and diverse foraminiferal assemblages including: *Neoarchaediscus, Cribrostomum, Bibradya, Koskinobigenerina,* and at the top, *Bradyina* and *Howchinia* (Conil *et al.* 1980; Fewtrell *et al.* 1981; Gallagher & Somerville 1997). The Brigantian (Cf6δ Subzone) is distinguished by the first appearance of large *Archaediscus karreri* group and *Loeblichia,* with *Janischewskina, Asteroarchaediscus, Tubispirodiscus, Planospirodiscus, Endothyranopsis sphaerica* and *Climacammina* appearing in the late Brigantian (Conil *et al.* 1980; Fewtrell *et al.* 1981; Somerville & Strank 1984b; Gallagher & Somerville 1997; Cózar & Somerville 2004; Cózar *et al.* 2005, 2006).

The youngest Mississippian *Eosigmoilina* (Cf7) Zone is not very well known in Western Europe because of mostly unfavourable facies, but equates with the Pendleian-Arnsbergian interval (Conil *et al.* 1980; 1990). The characteristic taxa for this zone include *Archaediscus* at *tenuis* stage, *Eosigmoilina robertsoni, Bradyina cribrostomata Loeblichia minima, Plectostaffella, Seminovella* and *Montaxinoides* spp. (Fewtrell *et al.* 1981; Conil *et al.* 1980; Somerville 2008). They are recorded rarely from Serpukhovian limestones in Scotland and northern England (e.g. Cummings 1961; Fewtrell *et al.* 1981; Riley 1992b; Cózar & Somerville 2004; Cózar *et al.* 2008, 2010; Stephenson *et al.* 2010).

Conodonts
Conodonts are present within marine facies, notably carbonate turbidites and hemi-pelagic shales, and conodont zones are particularly important for Tournaisian and Visean correlation (Rhodes *et al.* 1969; Austin 1973; Metcalfe 1981; Varker & Sevastopulo 1985). The range of selected conodonts in the Tournaisian and Visean of the British Isles (Fig. 3.3) is provided by Riley (1993), modified from Varker & Sevastopulo (1985), with broad-ranging conodont biozones also recognised within the Namurian. Distinct conodont biofacies are observed between the basinal and shelfal successions in Britain and Ireland, leading to two parallel zonations for Britain and Ireland.

The base of the Tournaisian Stage (former Series), and hence the Carboniferous System, has been redefined by Conil *et al.* (1977) to occur at the base of the *Siphonodella sulcata* Conodont Zone. The boundary between the former Hastarian and Ivorian stages of the Tournaisian is recognized as corresponding with the boundary

between the *Siphonodella* and *Polygnathus communis carina* biozones in conodonts (Ramsbottom & Mitchell 1980). The base of the Visean, although defined in the Pengchong section, South China, using foraminifers (Devuyst *et al.* 2003), also coincides approximately with the first appearance of *Gnathodus homopunctatus* which has a wide distribution (Perret & Weyant 1994). This taxon first appears slightly above the last occurrence of *Scaliognathus anchoralis* in many sections.

The Visean/Serpukhovian (Namurian) boundary is currently defined by the first appearance of *Lochriea ziegleri* (Nemyrovska 2005). Also, many authors equate the combined *Lochriea mononodosa* and *Gnathodus girtyi collinsoni* Biozones in the late Brigantian of Britain and Ireland with the *Lochriea nodosa* Zone (Skompski 1996; Somerville & Somerville 1999; Nemyrovska 2005; Somerville 2008), recognised throughout much of Western Europe.

The exact position of the mid-Carboniferous boundary between the Mississippian and Pennsylvanian has been defined as the appearance of the conodont *Declinognathodus noduliferus* (Wagner *et al.* 1985; Lane *et al.* 1985). This places the mid-Carboniferous boundary 9.4 m above the base of the Chokierian Substage (see Chapter 2).

Palynomorphs

Palynomorphs (miospores) are present in both marine and terrestrial environments and have been used for biozonation up to and including the Stephanian (Fig. 3.4). Palynomorphs have proved important zonal indicators in the Midland Valley of Scotland and the Northumberland Trough, where non-marine successions dominate. The first attempt to develop a palynostratigraphy for part of the British Carboniferous was for the Westphalian of north Staffordshire, Cannock Chase and North Wales coalfields (Butterworth & Millot 1955). The scheme was extended into the Namurian and Visean (Butterworth & Millot 1960), and further refined by Smith & Butterworth (1967), who recognised eleven palynomorph biozones for coal seams in Britain; seven biozones for the Westphalian, two for the Namurian and two for the Visean. A complete miospore zonation for the Tournaisian and Visean of Britain was proposed by Neves *et al.* (1972; 1973) and developed by Clayton *et al.* (1977; 1978). This zonal scheme is summarised in Figure 3.4. Further schemes have been proposed based upon palynomorph-bearing argillaceous strata (Neves *et al.* 1972; 1973; Owens & Burgess 1965). Other work has concentrated upon correlation with the well-defined ammonoid biostratigraphy (Neves 1961; Neves *et al.* 1965). Owens *et al.* (1977) produced a palynological zonation for the Namurian of northern England and Scotland. The palynological zonations for the Westphalian and Stephanian were summarised by Clayton *et al.* (1977), based on earlier work by Loboziak (1974).

The base of the *Vallatisporites vallatus-Retusotriletes incohatus* (VI) Miospore Zone equates with the base of the Tournaisian. The biostratigraphical position of the top of the *Kraeuselisporites hibernicus-Umbonatisporites distinctus* (HD) Zone and base of overlying *Spelaeotriletes balteatus-Rugospora polyptycha* (BP) Zone is unknown. The *Spelaeotriletes pretiosus-Raistrickia clavata* (PC) Zone in Ireland has a base just below the *Polygnathus inornatus* Conodont Zone and top within the *Pseudopolygnathus multistriatus* Conodont Zone. An interzone occurs between the PC Zone and the overlying *Schopfites claviger-Auroraspora macra* (CM) Zone (Riley 1993), the boundary being of late Tournaisian (Tn3) age (Higgs *et al.* 1988b). The base of the *Lycospora pusilla* (Pu) Zone is biostratigraphically imprecise. Originally

defined as containing the genus *Lycospora* (Neves *et al*. 1972) it has been redefined at the incoming of significant *L. pusilla* (Owens *et al*. 1977) or at the incoming of the first *L. pusilla* (Higgs *et al*. 1988b). The latter is more widely adopted, but Stephenson *et al*. (2004) outlined difficulties in the application of this approach. The *Knoxisporites triradiatus–K. stephanephorus* (TS) Zone was introduced by Clayton (1984) and assigned a late Arundian to mid-Holkerian age. However, the base of the overlying *Perotrilites tessellatus-Schulzospora campyloptera* (TC) Zone is now thought to lie within the early Asbian (Riley 1993). The *Raistrickia nigra-Triquitrites marginatus* (NM) Zone has been subdivided into the *Tripartites distinctus-Murospora parthenopia* (DP) and *Murospora margodentata-Rotaspora ergonulii* (ME) subzones by Clayton *et al*. (1978). The base of the NM Zone is chronostratigraphically imprecise, but is currently taken at the base of the late Asbian (Riley 1993). The base of the *Tripartites vetustus-Rotaspora fracta* (VF) Zone is recognised at the $P_{1a/b}$ ammonoid zonal boundary in northwest Ireland (Higgs 1984). The base of the *Reticulatisporites carnosus-Bellispores nitidus* (CN) Zone lies within the late Brigantian, between the upper part of the P_{2a} and P_{2b} ammonoid zones (Riley 1993).

Owens *et al*. (1977) produced a palynostratigraphy for the Namurian of northern England and Scotland, with 5 miospore biozones recognised encompassing the series (Fig. 3.4). Within the Central Pennine Basin palynomorph zones have been closely related to ammonoid zones. The CN Zone extends throughout the Pendleian, with an influx of new taxa at the base of the Pendleian allowing further subdivision of the biozone into the *Cingulizonates* cf. *capistratus* and *Verrucosisporites morulatus* Subzones (Owens *et al*. 2004). The base of the *Mooreisporites trigallerus-Rotaspora knoxi* (TK) Zone occurs near to the base of the Arnsbergian Substage (Owens *et al*. 2004). The base of the overlying *Lycospora subtriquetra-Kraeuselisporites ornatus* (SO) Zone has been recognised to occur at the High Wood Marine Band of the Stainmore area, considered to be located within the Arnsbergian E_{2b} ammonoid subzone. Owens *et al*. (2004) proposed a subdivision of the SO Biozone into a *L. subtriquetra-Apiculatisporis variocorneus* (SV) subzone extending from E_{2b} to the top of the Arnsbergian Substage and a *Lycospora subtriquetra-Cirratriradites rarus* (SR) subzone occupying the Chokierian and Alportian stages. The base of the *Crassispora kosankei-Grumosisporites varioreticulatus* (KV) Zone, previously taken at the base of the Kinderscoutian Substage, extending into early Marsdenian strata (Clayton *et al*. 1977), is now considered to commence during the late Alportian (Owens *et al*. 2004). The base of the *Raistrickia fulva-Reticulatisporites reticulatus* (FR) Zone, in the absence of constraining marine bands, has been taken to approximate to the mid-Marsdenian and extends to the base of the Westphalian Stage.

Miospore zonations have been developed for Westphalian coal seams by Smith & Butterworth (1967), but realise great importance within late Westphalian strata lacking alternative biostratigraphical correlations other than the macrofloras. The miospore zonation used in this report is that of Clayton *et al*. (1977) (Fig. 3.4). The *Triquitrites sinani-Cirratriradites saturni* (SS) Zone ranges from the Subcrenatum Marine Band to the boundary between the *lenisulcata* and *communis* non-marine bivalve zones. The *Radiizonates aligerens* (RA) Zone equates to the former Zone I of Ramsbottom *et al*. (1978) and the *Radiizonates aligerens* and *Schulzospora rara* Assemblage Zones of Smith & Butterworth (1967) and extends through the middle and upper parts of strata of Langsettian age (Clayton *et al*. 1977). The base of the *Microreticulatisporites nobilis-Florinites junior* (NJ) Zone corresponds with the

Vanderbeckei Marine Band, and the zone ranges throughout the Duckmantian Substage. The base of the overlying *Torispora securis-Torispora laevigata* (SL) Zone occurs slightly above the Aegiranum Marine Band, which marks the base of the Bolsovian Substage. The base of the *Thymospora obscura-Thymospora thiessenii* (OT) Zone equates with the base of the non-marine bivalve *Anthraconauta tenuis* Zone (Calver 1969), and is thus just below the base of the Asturian (Westphalian D) Substage (Cleal 1984).

The palynological recognition of the Westphalian – Stephanian stage boundary has long been contentious, largely because of the limited number of sections worldwide with well preserved palynofloras where the boundary could be independently located. Typically, throughout Europe there is a gradual palynological change across this boundary (Cleal *et al*. 2009). In the North Sea it appears to be impossible to recognise this boundary palynologically, whereas onshore in the British Isles there is the first appearance of *Westphalensisporites* in the Cantabrian (Cleal *et al*. 2009). Cleal *et al*. (2003) have shown that the boundary seems to coincide with the base of Zone XII established by Smith (1987) in the Oxfordshire Coalfield (probably equivalent to the base of the CP Zone of Peppers 1985), marked by the appearance of *Schopfites dimorphus* and a marked increase in abundance of *Thymospora pseudothiessenii* and *Cadiospora magna*. Based on unillustrated palynological records in Wagner & Spinner (1972), this would place the Westphalian – Stephanian boundary in the Household Coals Member, which would be compatible with the macrofloral evidence.

The *Angulisporites splendidus-Latensina trileta* (ST) Zone corresponding to the upper Barruelian and most of Stephanian B, the *Potonieisporites novicus-bhardwajii-Cheiledonites major* (NBM) Zone of the Stephanian C and D, the *Vittatina costabilis* (VC) Zone corresponding to the lower Autunian and the *Disaccites striatiti* (DS) Zone corresponding to the upper Autunian (Clayton *et al*. 1977) are all poorly represented in the British Isles.

Plant macrofossils
Initial attempts at a macrofloral biostratigraphical zonation were developed by Dix (1934) and recent advances have established the importance of plant fossil biostratigraphy (Fig. 3.5), particularly for the Asturian and Cantabrian (Wagner 1984; Cleal 1991). Numerous studies of the macrofloral record from individual coalfields have culminated in the production of key biostratigraphical descriptions of the zonations in the Variscan Foreland Basin of southern Britain (Cleal 1978, 1986b, 1987, 1997, 2007), for the Pennine Basin (Cleal 2005; 2008a), and in the broader context of coal basins extending from Novia Scotia to Bulgaria and including the Southern North Sea (Cleal *et al*. 2009). The region of southern Britain (South Wales, the Forest of Dean, Radstock and Oxfordshire) is unique within the Variscan Foreland Basin in including facies with abundant plant macrofossils from Bolsovian to Cantabrian age and occupies an intermediate palaeophytogeographical position between mainland Europe and North America (Cleal 2008b, 2008c). The late Westphalian to early Stephanian successions of the British Isles generally lack marine band and tonstein marker horizons, making macrofloral zonation of great importance in these successions, especially in the Variscan Foreland Basin where high coalification rank limit good preservation of pollen and spores (Cleal 1997). In contrast, north of the Wales-Brabant High, the presence of red-bed successions in the upper Bolsovian to Stephanian are associated with the extensive oxidation of plant

material, making macrofloral biostratigraphy difficult (Cleal & Thomas 1995), although recent re-evaluations of the available data have enabled some correlations to be proposed (Besly & Cleal 1997; Cleal 2005, 2008a).

The plant fossil biostratigraphy (Fig. 3.5) is largely based on development of assemblage biozones, founded on the ranges of plant fossil taxa, throughout the equatorial belt (Wagner 1984). There is no abrupt change in terrestrial vegetation between the Devonian and Carboniferous. Tournaisian and Visean plant fragments occur sporadically in Britain and the zones are wide-ranging and of limited correlation value. However, there are a number of classic adpression floras (e.g. from Teilia, Puddlebrook, Wardie) that all belong to the *Neuropteris antecedens* Zone (Cleal & Thomas 1995).

There is a broad distinction between plant fossil assemblages of Mississippian and Pennsylvanian age, probably reflecting initiation of Gondwanan ice-caps (Cleal & Thomas 1995). The Mid-Carboniferous boundary saw the decline or extinction of archaeocalamites and callamopityalean pteridosperms and the radiation of true ferns, the medullosalean pteridosperms and the cordaites (Cleal & Thomas 1995). Late Namurian plant fossils in Britain are commonly poorly reserved and in contrast with Westphalian flora are little studied, but can be assigned to the *Pecopteris aspera* Zone (Cleal & Thomas 1994).

The Westphalian fluvio-lacustrine deposits of the Coal Measures are particularly suited to the preservation of plant fossils (Cleal & Thomas 1995). The base of the *Lyginopteris hoeninghausii* Zone is formally placed at about the level of the base of the Westphalian Stage (Wagner 1984), although the changes in the macrofloras at this level are not particularly marked. More significant is the level recognised as the junction between the *Neuralethopteris jongmansii* and *Laveineopteris loshii* subzones within the *L. hoeninghausii* Zone, which is equivalent to the base of Zone D in Dix's (1934) scheme. This level in effect marks the start of the typical early Coal Measures floras, with the appearance of characteristic taxa such as *Laveineopteris* spp., *Neuropteris heterophylla*, *Lobatopteris miltoni*, *Mariopteris muricata* and *Eusphenopteris trifoliolata*.

The base of the *Lonchopteris rugosa* Zone is usually made to coincide with the base of the Duckmantian Substage, although there is no marked floral change at this level (Wagner 1984). It is sometimes stated that *Lyginopteris hoeninghausii*, *Karinopteris acuta* and *Neuralethopteris* spp., taxa that are characteristic of the Langsettian and earlier macrofloras, become extinct at this level, but they in fact usually disappear from the stratigraphical record at rather lower (usually middle Langsettian) levels. Cleal (1991) suggested that the *L. rugosa* Zone could be subdivided into two subzones, but subsequent analyses of the data have not supported this (Cleal 2005, 2007).

The *Paripteris linguaefolia* Zone marks a significant change in the macrofloras with the appearance of a number of species characteristic of the upper Westphalian Stage. The change occurs in two distinct steps, reflected in the division of the zone into two subzones. The base of the lower, *Neuropteris semireticulata* Subzone is marked by the appearances of *N. semireticulata*, *Macroneuropteris scheuchzeri*, *Mariopteris nervosa* and *Eusphenopteris striata*, and usually occurs at about the level where

marine bands start to make their re-appearance at about the level of the Maltby Marine Band (Cleal *et al.* 2009). The base of the *Laveineopteris rarinervis* Subzone is marked by the appearance of *L. rarinervis, Sphenophyllum emarginatum, Annularia sphenophylloides* and *A. spinulosa* (= *A. stellata*), and usually coincides approximately with the Edmondia Marine Band in South Wales and Shafton Marine Band within the Pennine Basin (Cleal *et al.* 2009), in the middle Bolsovian Substage. This latter level is equivalent to the base of Dix's (1934) Zone G. This marks a major change in the terrestrial habitats and biotas and corresponds to the base of Kidston's (1905) Staffordian 'Series' and of Dix & Trueman's (1937) Morganian Substage. The base of the Bolsovian Substage cannot be identified based on the macrofloras.

The base of the Asturian Substage is indicated by the base of the *Linopteris bunburii* Zone (equivalent to the *L. obliqua* Zone of Wagner (1984). This zonal boundary is mainly identified by the appearance of the single taxon *Neuropteris ovata* (Cleal *et al.* 2009), although Laveine (1977) listed a series of other criteria that could also be used to help place the boundary (see also Cleal 1984, Cleal *et al.* 2009).

The *Lobatopteris vestita* Zone in the mid–late Asturian Substage sees a marked diversification of alethopterid medullosalean pteridosperms and marattialean ferns (Cleal 2007), and the appearance of callistophytalean pteridosperms (*Dicksonites*). The appearance of these macrofloras, of essentially Stephanian aspect, occurs in two distinct steps, distinguished as subzonal boundaries: the base of the *L. micromiltoni* Subzone is marked by the appearance of *Alethopteris serlii, A. ambigua* and *A. pseudograndinioides*, and a significant increase in abundance of *L. micromiltoni* and *Cyathocarpus* spp.; the base of the *D. plueckenetii* Subzone is marked by the appearance of *D. plueckenetiii, Acitheca polymorpha* and *L. vestita* auct (Cleal *et al.* 2009).

The base of the Stephanian Stage (and thus of the Cantabrian Substage) is placed at the base of the *Odontopteris cantabrica* Zone (Cleal *et al.* 2003). This boundary is marked by the appearance of several taxa, notably *Odontopteris brardii, O. cantabrica* and *Sphenophyllum oblongifolium*, although none of these species is particularly common in Britain. Stephanian plant fossils are rare in Britain, mainly limited to the Forest of Dean (Wagner & Spinner 1972; Cleal 1986a), South Wales (Cleal 1997, 2007) and the southern Pennines (Cleal 2008a).

Corals
Coral biozonation has been of historical importance in the classification of Tournaisian and Visean platform carbonates, though they are now considered strongly facies controlled. Zones based upon coral assemblages were defined by Vaughan (1905) from the Bristol area, to the south of the Wales-Brabant High. These zones could not be readily correlated to the north of the Wales-Brabant High and are now considered assemblage biozones. Garwood (1913) initiated a comparable zonation for northern Britain, defined by faunal marker bands. The index names used for these zones, shown in Fig. 3.6 are still widely referred to in modern literature.

Tournaisian zones were revised as assemblage biozones by Ramsbottom & Mitchell (1980), Mitchell (1981) and Sevastopulo & Nudds (1987). The late Tournaisian is marked by the incoming of several taxa including: *Caninia cornucopiae,*

Caninophyllum patulum, *Cyathoclisia modavensis* and *Siphonophyllia* sp. (Mitchell & Somerville 1988; Somerville 1994).

The distribution of Visean rugose corals is summarized by Mitchell (1989). A slightly modified version of the range of Visean rugose corals was provided in Riley 1993. The base of the *Siphonophyllia cylindrica* Biozone of Ramsbottom & Mitchell (1980) correlates closely with the base of the Visean Stage. *Dorlodotia pseudovermiculare* is limited to Chadian age, replaced in the Arundian by *D. briarti*. Chadian faunas (Assemblage A of Mitchell (1989), also include *Carruthersella compacta*, *Spirophyllum praecursor*, *Sychnoelasma hawbankense* and *S. urbanbowitschi* (Mitchell & Somerville 1988).

The Arundian succession of South Cumbria is recognised to have three faunal divisions (Assemblages B to D of Mitchell (1989)), corresponding to the Red Hill Limestone Formation, lower and middle part of the Dalton Formation and upper part of the Dalton Formation, respectively (Rose & Dunham 1977). Arundian taxa include: *Clisiophyllum multiseptatum*, *Siphonodendron martini*, *S. sociale*, *Siphonophyllia caninoides* and *S. garwoodi* (Somerville *et al*. 1986).

The base of the Holkerian Substage is defined as the lithological change that occurs below the incoming of diagnostic corals *Axophyllum vaughani* and *Clisiophyllum rigidum* at the base of the stratotype. Holkerian coral assemblages (Assemblage E of Mitchell (1989)) are dominated by *Lithostrotion araneum* (formerly *L. minus*), often associated with *L. vorticale* (= *L. arachnoideum* and *L. portlocki* in Mitchell 1989) (Nudds 1981).

Asbian faunas are distinctive and can be used to subdivide the lower and upper Asbian successions. The base of the Asbian Substage was defined by George *et al*. (1976) as the lithological change that occurs below the incoming of diagnostic early Asbian corals (Assemblage F of Mitchell (1989)), which include *Dibunophyllum bourtonense*, *Siphonodendron pauciradiale*, *Lithostrotion decipiens* and *Siphonophyllia benburbensis*. Aretz and Nudds (2005) provide a detailed description of the coral assemblages present at the stratotype. Late Asbian corals (Assemblage G of Mitchell (1989)) are much more diverse and include *Dibunophyllum bipartitum*, *Siphonodendron junceum*, *Lithostrotion maccoyanum*.

The Brigantian contains the richest and most varied British Visean coral faunas, with three faunal zones recognised for the early Brigantian (Assemblages H to J) and one for the late Brigantian (Assemblage K of Mitchell 1989). The Brigantian Substage records the incoming of diagnostic coral fauna including, *Actinocyathus floriformis*, *Corwenia rugosa*, *Diphyphyllum lateseptatum*, *Nemistium edmondsi*, *Orionastraea* spp. and *Palastraea regia*.

Brachiopods
Early correlations, typified by Vaughan (1905) used brachiopods along with corals to establish faunal zones for the Tournaisian and Visean. Although brachiopods are one of the most common elements of Mississippian marine sediments their distribution is controlled by palaeoecological factors, so that although some brachiopod species are widely distributed, most are endemic with different, locally dominant, species. These widely dispersed individual species continue to be considered locally important markers

for particular horizons, e.g. *Syringothyris* cf. *cuspidata* and the associated fauna have been used to delineate the base of the Chadian in the Scottish Borders. However, the association of specific brachiopods with particular facies make them of limited use for widespread correlation. Attempts have been made to assess the usefulness of brachiopods in worldwide (Brunton 1984a) and western European (Legrand-Blain 1990) correlation, and both studies highlighted the need for the revision of several genera such as *Spirifer* and *Productus*.

George *et al*. (1976) listed various brachiopods as characteristic of different Tournaisian and Visean substages (Fig. 3.7) based on Vaughan (1905). However, various taxonomic studies have indicated that some of these brachiopods may have longer ranges than originally suggested and are not restricted to the substages they were originally said to characterise (Fig. 3.7). Other brachiopods e.g. *Delepinea carinata* which has a widespread geographic range, but is restricted to the Arundian, and *Davidsonina septosa,* in the late Asbian to early Brigantian, are of biostratigraphic importance. An attempt to assess the usefulness of *Gigantoproductus*, *Semiplanus* and *Latiproductus* for stratigraphic correlation through the Visean and Namurian was made by Pattison (1981). Although some species appear to be restricted to single substages they are not widespread either within, or between, basins. Furthermore, certain morphological features appear to be phenotypically rather that genotypically controlled, making taxonomic assignments difficult.

Visean brachiopod faunas have been particularly extensively described (Brunton 1966, 1968, 1982, 1984a, 1984b; Brunton & Mundy 1986; Brunton & Tilsley 1991). These studies have revealed a fauna with elements that were especially adapted to certain niches on the Carboniferous shelf and reefs of Derbyshire, Staffordshire, Yorkshire and County Fermanagh (Northern Ireland). Other elements of the fauna e.g. *Vitiliproductus wedberensis* (Brunton & Mundy 1988) from Derbyshire (and possibly County Clare, western Ireland) show similarities with NW Australia, China and questionably Kazakhstan.

Brachiopods are not used in the Namurian to Stephanian for stratigraphic purposes, being poorly documented with few taxonomic studies having been made (Calver 1968; Wilson 1967; Pattison 1981). From the end of the Visean, brachiopods became scarce both in Britain and NW Europe. *Lingula* bands representing marine incursions during the Namurian, Langsettian and Duckmantian form distinct horizons across northern England and Scotland. Richer marine bands are also found and these include productoid and other brachiopods. These are most common in the early Namurian.

Algae
Calcareous algae are common within carbonates, notably in shallow-water shelf limestones of the Visean in the British Isles, especially the Asbian and Brigantian substages (Hallett 1970; Adams *et al*. 1992; Johnson & Nudds 1996; Gallagher & Somerville 1997; Cózar & Somerville 2004; Cózar *et al*. 2005). In the late Tournaisian green algae are very sparse with *Atractyliopsis* and *Koninckopora* (monolaminar), together with aoujgaliids (red algae), occurring notably in mudmounds (Somerville 2003). Rare problematica include *Sphaerinvia* and *Salebra* (Jones & Somerville 1996). In the Visean the first appearance of bilaminar forms of *Koninckopora* are reported in the Chadian (Davies *et al*. 1989; Somerville *et al*. 1989; Strogen *et al*. 1990) and the virtual extinction of *Koninckopora* marks the base of the

Brigantian Substage (Somerville & Strank 1984b; Riley 1993; Cózar & Somerville 2004; Cózar *et al.* 2005). In the Arundian *Nanopora fragilissima* is first recorded (Legg *et al.* 1998) and in the Holkerian *Draffania biloba* (Problematicum) first appears. In the Asbian a rich and diverse algal assemblage is recorded with abundant palaeoberesellids (*Kamaena* and *Kamaenella*), aoujgaliids (*Ungdarella*) and dasyclads (*Kulikia, Pseudokulilia*). In the latest Asbian *Coelosporella, Eovelebitella* and *Koninckopora* sp. first appear (Gallagher & Somerville 1997; Cózar & Somerville 2004; Cózar *et al.* 2005). The early Brigantian is marked by the first appearance of *Falsocalcifolium punctatum* and the red alga *Neoprincipia* (Somerville 2008). In the late Brigantian and Pendleian *Calcifolium okense* is the dominant codiacean alga (Burgess 1965; Hallet 1970; Cózar & Somerville 2004; Cózar *et al.* 2005, 2008, 2010; Somerville 2008).

Cyanophytes (so-called 'blue-green' algae) are also recorded in the non-marine to peritidal limestones of the Midland Valley of Scotland and northern England. The base of the Arundian in the Scottish Borders is taken at the base of a nodular algal band, the Hillend Algal Band of Bewcastle (George *et al.* 1976).

Bivalves
In the Tournaisian, Visean and Namurian, marine bivalves present within hemipelagic shales and occurring in association with ammonoids are of some stratigraphical importance (Riley 1993). The mytiloid *Aviculomya* is present in the Chadian *Fascipericyclus-Ammonellipsites* Ammonoid Zone. In the *Beyrichoceras* Ammonoid Zone, *Posidoniella vetusta* is characteristic of the 'knoll reef' setting and *Actinopteria persulcata*, *Dunbarella persimilis*, *Posidonia kochi* and *P. corrugata*, enter in hemipelagic mudstones within this zone. *Posidonia becheri* is abundant in P_{1b} and P_{1c} ammonoid zones, though rare in the P_{1d} Zone, within which *P. membranacea* and *P. trapezoedra* become abundant.

In the late Namurian and Westphalian regional stages, non-marine bivalves assume greater biostratigraphical importance. Non-marine bivalve biozones for the Westphalian were defined by Trueman & Weir (1946), though with time the zonal boundaries have been fixed at prominent coals or marine bands and recognised as chronozones (see Fig. 3.8). The zonation is of particular importance in correlation of Westphalian strata that lack marine bands and adequate floral records.

Ostracodes
Ostracodes are common in late Tournaisian and Visean marine and lacustrine settings. Namurian and Westphalian successions contain little in the way of stratigraphically important ostracodes, the exception being the Pendleian and Arnsbergian strata of the Yoredale Group of northern England (Robinson 1978). Two distinct ostracode faunas are recognised, a benthic fauna which inhabited shallow-water conditions associated with structural highs ("blocks") and epiplanktonic ostracodes present within the more rapidly subsiding basins. Most stratigraphical work has been carried out on benthic ostracodes, though the assemblages are highly controlled by water depth and salinity (Robinson 1978). Most recorded assemblages come from mudstones, from which ostracodes are more easily extracted. Consequently, they have little practical application to the carbonate-dominated successions of Tournaisian and Visean age. A locally applicable ostracode zonation for the Northumberland Trough and Midland Valley of Scotland has been developed by Robinson (1978).

Trilobites

Trilobites are locally common in Tournaisian and Visean hemipelagic mudstones, bioherms and carbonate ramp/platform settings and present within some Namurian and Westphalian marine bands. In Southwest England much emphasis has been placed on the trilobite biozones erected in Germany (see Chapter 4), though they have greatest resolution within Tournaisian and latest Visean strata. Owens (1984) provided a review of research and range chart, with key monographs provided by Owens (1986) and Osmólska (1970).

Fig. 3.1a Ammonoid biozonation based on Riley (1993) for the Tournaisian and Visean, Riley *et al*. (1995) for the Namurian. Fig. 3.1b Westphalian marine bands from Ramsbottom *et al*. (1978).

Fig. 3.2 Foraminiferal biozonation for the Tournaisian and Visean based Riley (1993), adapted from Conil *et al*. (1980, 1990) and Jones & Somerville (1996).

Fig. 3.3 Conodonts biozonation for the Tournaisian and Visean from Riley (1993), modified from Varker & Sevastopulo (1985), and Namurian from Riley *et al*. (1995).

Fig. 3.4 Miospore biozonation for the Carboniferous based on Clayton *et al*. (1977; 1978), showing former zonation of Owens *et al*. (1977) and Ramsbottom *et al*. (1978), and modifications to the scheme by Clayton (1984) and Owens *et al*. (2004).

Fig. 3.5 Macrofloral biozonation for the Carboniferous based on Cleal (1991).

Fig. 3.6 Coral biozonation schemes of Vaughan (1905) for the Bristol area, Garwood (1913) for northern England and Mitchell (1981, 1989), modified from Riley (1993).

Fig. 3.7 Brachiopods considered typical of Tournaisian and Visean substages and their possible ranges outside the substage of which they are supposedly diagnostic.

Fig.3.8 Non-marine bivalve chronozones for the Westphalian (after Trueman & Weir 1946).

REGIONAL STAGES	REGIONAL SUBSTAGES	ZONES		WESTERN EUROPEAN MARINE BANDS	
		Index	Ammonoid	Index	Ammonoid
WESTPHALIAN	Langsettian (pars)		*Gastrioceras listeri*		
		G2	*Gastrioceras subcrenatum*		
NAMURIAN	Yeadonian	G1b	*Cancelloceras cumbriense*	G1b1	*Ca. cumbriense*
		G1a	*Cancelloceras cancellatum*	G1a1	*Ca. cancellatum*
	Marsdenian	R2c	*Bilinguites superbilinguis*	R2c2	*Verneulites sigma*
				R2c1	*B. superbilinguis*
		R2b	*Bilinguites bilinguis*	R2b5	*B. metabilinguis*
				R2b4	*B. eometabilinguis*
				R2b3	*B. bilinguis*
				R2b2	*B. bilinguis*
				R2b1	*B. bilinguis*
		R2a	*Bilinguites gracilis*	R2a1	*B. gracilis*
	Kinderscoutian	R1c	*Reticuloceras reticulatum*	R1c4	*R. coreticulatum*
				R1c3	*R. reticulatum*
				R1c2	*R. reticulatum*
				R1c1	*R. reticulatum*
		R1b	*Reticuloceras eoreticulatum*	R1b3	*R. stubblefieldi*
				R1b2	*R. nodosum*
				R1b1	*R. eoreticulatum*
		R1a	*Hodsonites magistrorum*	R1a5	*R. dubium*
				R1a4	*R. todmordenense*
				R1a3	*R. subreticulatum*
				R1a2	*R. circumplicatile*
				R1a1	*Ho. magistrorum*
	Alportian	H2c	*Vallites eostriolatus*	H2c2	*Homoceratoides prereticulatus*
				H2c1	*V. eostriolatus*
		H2b	*Homoceras undulatum*	H2b1	*H. undulatum*
		H2a	*Hudsonoceras proteum*	H2a1	*Hd. proteum*
	Chokierian	H1b	*Homoceras beyrichianum*	H1b2	*Isohomoceras.* sp. nov.
				H1b1	*H. beyrichianum*
		H1a	*Isohomoceras subglobosum*	H1a3	*I. subglobosum*
				H1a2	*I. subglobosum*
				H1a1	*I. subglobosum*
	Arnsbergian	E2c	*Nuculoceras stellarum*	E2c4	*N. nuculum*
				E2c3	*N. nuculum*
				E2c2	*N. nuculum*
				E2c1	*N. stellarum*
		E2b	*Cravenoceratoides edalensis*	E2b3	*Ct. nititoides*
				E2b2	*Ct. nitidus*
				E2b1	*Ct. edalensis*
		E2a	*Cravenoceras cowlingense*	E2a3	*Eumorphoceras yatesae*
				E2a2a	*C. gressinghamense*
				E2a2	*Eumorphoceras ferrimontanum*
				E2a1	*C. cowlingense*
	Pendleian	E1c	*Cravenoceras malhamense*	E1c1	*C. malhamense*
		E1b	*Cravenoceras brandoni*	E1b2	*Tumulites pseudobilinguis*
				E1b1	*C. brandoni*
		E1a	*Cravenoceras leion*	E1a1	*C. leion*
VISEAN	Brigantian	P2c	*Lyrogoniatites georgiensis*		
		P2b	*Neoglyphioceras subcirculare*		
		P2a	*Lusitanoceras granosus*		
		P1d	*Paraglyphioceras koboldi*		
		P1c	*Paraglyphioceras elegans*		
		P1b	*Arnsbergites falcatus*		
	Asbian	P1a	*Goniatites crenistria*		
		B2b	*Goniatites globostriatus*		
		B2a	*Goniatites hudsoni*		
	Holkerian	B1			
	Arundian	BB	*Bollandites-Bollandoceras*		
	Chadian	FA	*Fascipericyclus-Ammonellipsites*		
TOURNAISIAN	Courceyan		*Pericyclus*		
			Gattendorfia subinvoluta		

AGE	STANDARD NAMES
BOLSOVIAN	Cambriense
	Shafton
	Edmondia
	Aegiranum
DUCKMANTIAN	Sutton
	Haughton
	Clown
	Maltby
	Vanderbeckei
LANGSETTIAN	Burton Joyce
	Langley
	Amaliae
	Meadow Farm
	Parkhouse
	Listeri
	Honley
	Springwood
	Holbrook
	Subcrenatum

	STANDARD NAMES
BOLSOVIAN	Cambriense
	Shafton
	Edmondia
	Aegiranum
DUCKMANTIAN	Sutton
	Haughton
	Clown
	Maltby
	Vanderbeckei
LANGSETTIAN	Burton Joyce
	Langley
	Amaliae
	Meadowfarm
	Parkhouse
	Listeri
	Honley
	Springwood
	Holbrook
	Subcrenatum

STAGES	SUBSTAGES		INDEX	ZONES	SUBZONES
SERPUK-HOVIAN	Arnsbergian		Cf7	*Eosigmoilina*	
	Pendleian				
VISEAN	Brigantian	late	Cf6	*Neoarchaediscus*	δ
		early			
	Asbian	late			γ
		early			α-β
	Holkerian		Cf5	*Koskinotextularia – Pojarkovella nibelis*	
	Arundian	late	Cf4	*Eoparastaffella*	δ
		mid			γ
		early			β
	Chadian				α2
TOURN-AISIAN	Courceyan				α1
			Cf3	*Tetrataxis – Eotextularia diversa*	α2
					α1
			Cf2	*Paraendothyra*	
			Cf1	*Chernyshinella*	

STAGES	SUBSTAGES	CONODONTS			
		Index	Zone	Zone (basin)	Zone (Shelf)
WEST-PHALIAN	Langsettian (pars)			*Idiognathoides sulcatus parvus*	
				Idiognathoides sinuatus – Idiognathoides primulus	
NAMURIAN	Yeadonian				
	Marsdenian				
	Kinderscoutian			*Idiognathoides corrugatus – Idiognathoides sulcatus*	
	Alportian			*Declinognathus noduliferus*	
	Chokierian				
	Arnsbergian			*Gnathodus bilineatus bollandensis*	
	Pendleian			*Kladognathus – Gnathodus girtyi simplex*	
VISEAN	Brigantian		*Gnathodus bilineatus*		*Gnathodus girtyi collinsoni*
					Lochriea mononodosa
	Asbian				*Gnathodus bilineatus*
	Holkerian	*Cc4β*	*Mestognathus praebeckmanni*	Informal unit with taphrognathids	*Lochriea commutata*
	Arundian			*Lochriea commutata*	
	Chadian	*Cc4α*		*Gnathodus homopunctatus*	*Gnathodus homopunctatus*
				Mestognathus praebeckmanni	
TOURNAISIAN	Courceyan	*Cc3γ*	*Scaliognathus anchoralis*	*Scaliognathus anchoralis – Polygnathus bischoffi*	*Polygnathus – mehli*
		Cc3β		*Eotaphrus burlingtonensis*	
		Cc3α		*Doliognathus latus*	
		Cc2δ	*Polygnathus Communis carina*	*Dollymae bouckaerti*	
		Cc2γ		*Eotaphrus bultyncki*	
		Cc2β		*Eotaphrus cf. bultyncki*	
		Cc2α		*Dollymae hassi*	*Pseudopolygnathus multistriatus*
		Cc1	*Siphonodella*	*Siphonodella sulcata*	*Polygnathus inornatus*
					Polygnathus spicatus

STAGES	SUBSTAGES	FORMER INDEX	INDEX		ZONES	SUBZONE
AUTUNIAN	Lower Autunian		VC		*Vittatina costabilis*	
STEPHANIAN	Stephanian C	XII	NBM		*Potonieisporites novicus-bhardwajii-Cheiledonites major*	
	Stephanian B					
	Barruelian		ST		*Angulisporites splendidus-Latensina trileta*	
	Cantabrian		OT		*Thymospora obscura-T. thiessenii*	
WESTPHALIAN	Asturian	XI				
	Bolsovian	X	SL		*Torispora securis- T. laevigata*	
		IX	NJ		*Microreticulatisporites nobilis-Florinites junior*	
	Duckmantian	VIII				
		VII				
	Langsettian		RA		*Radiizonates aligerens*	
		VI				
		SS	SS		*Triquitrites sinani-Cirratriradites saturni*	
NAMURIAN	Yeadonian	FR	FR		*Raistrickia fulva-Reticulatisporites reticulatus*	
	Marsdenian					
	Kinderscoutian	KV	KV		*Crassispora kosankei-Grumosisporites varioreticulatus*	
	Alportian	SO				
	Chokierian		SO	SR	*Lycospora subtriquetra-Kraeuselisporites ornatus*	*L. subtriquetra-Cirratriradites rarus*
	Arnsbergian			SV		*L. subtriquetra-Apiculatisporis variocorneus*
		TK	TK		*Mooreisporites trigallerus-Rotaspora knoxi*	
	Pendleian	NC	CN	Vm	*Reticulatisporites carnosus-Bellispores nitidus*	*Verrucosisporites morulatus*
VISEAN	Brigantian			Cc		*Cingulizonates* cf. *capistratus*
		VF	VF		*Tripartites vetustus-Rotaspora fracta*	
	Asbian	NM	NM	ME	*Raistrickia nigra-Triquitrites marginatus*	*Murospora margodentata-Rotaspora ergonulii*
				DP		*Tripartites distinctus-Murospora parthenopia*
		TC	TC		*Perotrilites tessellatus-Schulzospora campyloptera*	
	Holkerian		TS		*Knoxisporites triradiatus-Knoxisporites stephanephorus*	
	Arundian	Pu				
	Chadian		Pu		*Lycospora pusilla*	
TOURNAISIAN	Courceyan	CM	CM		*Schopfites claviger-Auroraspora macra*	
			PC		*Spelaeotriletes pretiosus-Raistrickia clavata*	
		VI	BP		*Spelaeotriletes balteatus-Rugospora polyptycha*	
			HD		*Kraeuselisporites hibernicus-Umbonatisporites distinctus*	
			VI		*Vallatisporites vallatus-Retusotriletes incohatus*	

STAGES	SUBSTAGES	ZONES	SUBZONE
STEPHANIAN	Cantabrian	*Odontopteris cantabrica*	
WESTPHALIAN	Asturian	*Lobatopteris vestita*	*Dicksonites plueckenetii*
			Lobatopteris micromiltoni
		Linopteris bunburii	
	Bolsovian	*Paripteris linguaefolia*	*Laveineopteris rarinervis*
			Neuropteris semireticulata
	Duckmantian	*Lonchopteris rugosa*	
	Langsettian	*Lyginopteris hoeninghausii*	*Laveineopteris loshii*
			Neuralethopteris jongmansii
NAMURIAN	Yeadonian	*Pecopteris aspera*	*Neuralethopteris larischii*
	Marsdenian		*Sigillaria elegans*
	Kinderscoutian		
	Alportian		
	Chokierian		
	Arnsbergian	*Lyginopteris larischii*	
		Lyginopteris stangeri	
	Pendleian	*Neuropteris antecedens*	*Lyginopteris fragilis*
VISEAN	Brigantian		*Diplopteridium*
	Asbian	*Triphyllopteris*	*Spathulopteris*
	Holkerian		
	Arundian		*Lepidodendropsis*
	Chadian		
TOURNAISIAN	Courceyan	*'Adianites'*	

STAGES	SUBSTAGES		Mitchell (1981, 1989) Zones	Vaughan (1905) Zones	Vaughan (1905) Subzones	Garwood (1913) Zones	Garwood (1913) Subzones
VISEAN	Brigantian	late	K	Є		*Dibunophyllum* (D)	*D. muirheadi* (Dγ)
		early	J	*Dibunophyllum* (D)	*Lonsdaleia* (D2)		*Lonsdaleia floriformis* (D$_2$)
			I				
			H				
	Asbian	late	G		θφ (D1)		*Cyathophyllum murchisoni* (D$_1$)
		early	F				
	Holkerian		E	*Seminula* (S)	S$_2$ (part)	*Productus corrugato hemisphericus* (S)	*Nematophyllum minus Cyrtina carbonaria* (S$_2$)
	Arundian	late	D		S$_2$ (part)		S$_1$
					S$_1$		
					C$_2$ (part)		
		mid	C	*Syringothyris* (C)		*Michelinia grandis*	*C. carinata C. isorhyncha* C$_2$ (part)
		early	B				
	Chadian		A		C$_2$ (part)	*Athyris glabristria*	C$_2$ (part)
					C$_1$		C$_1$
TOURNAISIAN	Courceyan	'Ivorian'	*Siphonophyllia cylindrica*				
			Caninophyllum patulum				
			Zaphrentites delanouei	*Zaphrentis* (Z)	γ	Z ?	
					Z$_2$		
					Z$_1$		
					β		
		'Hastarian'	*Vaughania vetus*	*Cleistopora* (K)	K$_2$		
					K$_2$		
				Modiola (M)			

| SUBSTAGES | NON-MARINE BIVALVES | |
	ZONES	SUB-ZONES
Cantabrian	*Anthraconauta tenuis*	
Asturian		
Bolsovian	*Anthraconauta phillipsi*	
	`*Upper similis-pulchra'*	
		adamsi-hindi
Duckmantian	`*Lower similis-pulchra'*	*atra*
		caledonica
		phrygiana
	Anthraconaia modiolaris	*ovum*
		regularis
		cristagalli
Langsettian	*Carbonicola communis*	*pseudorobosta*
		bipennis
		torus
	Carbonicola lenisulcata	*proxima*
		extenuata
		fallax-protea

SUBSTAGE	TYPICAL BRACHIOPODS (George *et al*. 1976)	PRESENCE IN OTHER SUBSTAGES
Brigantian	***Productus hispidus***	**Asbian (1;2)**
	Productus productus	Pendleian (8;9)
	Pugilis pugilis	Asbian (5); Pendleian (10)
Asbian	***Linoprotonia hemisphaerica***	**Holkerian, Brigantian (11)**
	Daviesiella llangollensis	Holkerian (6)
	Davidsonina septosa	Brigantian (4;7)
Holkerian	***Davidsonina carbonaria***	**Asbian (6)**
	Composita ficoides	**Arundian (5)**
	Linoprotonia corrugatohemisphaerica	
Arundian	***Delepinea carinata***	
	Delepinea destinezi	
	Pustula pyxidiformis	Asbian (1; 2)
Chadian	***Levitusia humerosa***	
Courceyan	*Avonia bassa*	
	Brochocarina wexfordensis	Chadian (12); Asbian (3)
	Camarotoechia mitcheldeanensis	
	Unispirifer tornacensis	

Fig. 12. Brachiopods considered typical of Tournaisian and Visean substages and their possible ranges outside the substage of which they are supposedly diagnostic. Characteristic brachiopods shown in bold. (1) Mitchell in Stevenson & Gaunt (1971); (2) Brunton & Tilsley (1991); (3) Brunton (1968); (4) Somerville & Strank (1984a); (5) Riley (1995); (6) Strank in Arthurton *et al.* (1988); (7) Chisholm *et al.* (1983); (8) Pattison in Burgess & Holliday (1979); (9) Arthurton *et al.* (1988); (10) Dunham & Wilson (1985); (11) Mitchell in Aitkenhead *et al.* (1985); (12) Ramsbottom (1981).