Chapter 1 Introduction and general background

The Upper Carboniferous must rank as one of the most significant parts of the geological column in Britain. Economically, this is a consequence of the coal, iron and clay reserves that it contains, and which were central to the development of Britain as a major world power during the late 18th and 19th centuries. In the mid-1980s home-produced coal was still providing over two-thirds of the electricity generated here, although recent political moves will mean that this dependency may soon cease.

The British Upper Carboniferous is also important for purely scientific reasons. The first use of the term Carboniferous was in a description of British geology by Conybeare and Phillips (1822), and according to Ramsbottom (1981, 1984) this country may in effect be regarded as the 'type district' for the system. For a time, continental Europe took over as the conceptual type of the Upper Carboniferous, largely through the efforts of Munier Chalmas and de Lapparent (1893) who introduced the terms Westphalian and Stephanian (based on the successions in Westfalia in Germany and St Etienne in France), which are still used as the names for two of the series (see Wagner, 1974 for further historical details). These parts of northern continental Europe suffer from generally poor exposure though, and so the IUGS Subcommission on Carboniferous Stratigraphy (the internationally-recognized organization that is trying to standardize the classification of these strata) has returned to Britain in its search for Upper Carboniferous stage stratotypes. Now, all eight stages between the Chokierian and Bolsovian inclusive are defined by stratotypes in this country (Ramsbottom, 1981; Owens *et al.,* 1985). In no other subsystem has Britain so many internationally-recognized stage stratotypes.

British geologists have been at the forefront of scientific work on the Upper Carboniferous, particularly in biostratigraphy. Significant names include W. Hind, A.E. Trueman, J. Weir, D. Leitch, and more recently R.M.C. Eagar and F.M. Broadhurst for their work on non-marine bivalves; W.S. Bisat, R.G.S. Hudson and W.H.C. Ramsbottom for their work on goniatites; M.A. Calver for his work on marine band distributions; R. Kidston, E. Dix and R. Crookall for their biostratigraphical palaeobotany; and the palynologists A.H.V. Smith, M.A. Butterworth, R. Neves and B. Owens. All of these scientists have made internationally significant contributions to Upper Carboniferous palaeontology and biostratigraphy, based mainly on work on British sites. Until recently, the sedimentology of the British Upper Carboniferous was not so widely studied. Over the last four decades, however, the situation has changed with major contributions having been made by geologists such as H.G. Reading, J.R.L. Allen, W.A. Read, G. Kelling and J.D. Collinson.

Britain can also boast some of the best exposed sequences of non-marine Upper Carboniferous strata anywhere in Europe. Nowhere else has such extensive coastal exposures of these beds, as can be seen in Pembrokeshire, Northumberland, Cumbria and Fife. Even outside of Europe, one would struggle to find comparable coastal exposures, at least within the palaeoequatorial belt, with the possible exception of Nova Scotia in Canada (e.g. Joggins Bank, Point Aconi). Britain is also unusually well endowed with natural, inland exposures. For instance the Pennines is a classic area for Namurian studies, with their extensive exposures of Millstone Grit. In the Westphalian, South Wales stands unrivalled (at least in Europe) for its well exposed sequences of mainly non-marine, coal-bearing strata; for example, this is the only place to have a more or less continuously exposed section through the Langsettian, Duckmantian and Bolsovian (Cwm Gwrelych–Nant Llyn Fach — see Chapter 4).

All-in-all, British sites are of prime importance in the study of Upper Carboniferous stratigraphy, and there is considerable incentive for their conservation. Partly, this is because of the historical role that they have played. However, the suite of stage stratotypes here means that Britain must play an ongoing role in the development of the science. This not only requires that the stratotypes themselves are protected, but also the rest of the network of sites, as these provide the vital sedimentological, palaeoecological and structural context in which the stratotypes have to be viewed, if they are to be properly understood.

Scope of this volume

Before progressing further, it is important to clarify the scope of this volume. It deals with sites in Great Britain (i.e. England, Scotland and Wales, but excluding the Channel Islands, Northern Ireland and the Isle of Man) showing significant features of Upper Carboniferous stratigraphy. They comprise the network of GCR Sites selected for this part of the stratigraphical column, and which have been (or will be) used to form Earth science Sites of Special Scientific Interest (SSSIs). A further discussion on the status of such sites can be found in Wimbledon (1988) and Allen *et al.* (1989).

There has been much confusion as to the exact meaning of the term Upper Carboniferous. In northern Europe, it has been taken to include all of the Namurian, Westphalian and Stephanian stages (now series), as this represents an interval of largely fluvio-deltaic elastics, which can be readily separated from the mainly marine shelf limestones of the underlying Viséan. Elsewhere, however, Lower and Upper Carboniferous were used in a different context. In North America, for instance, the base of what they call the Pennsylvanian is placed rather higher in the Namurian, in the lower Chokierian Stage (Sutherland and Manger, 1984). In eastern Europe, such as in the Ukraine and Russia, the situation is further complicated by the use of a tripartite division of the Carboniferous; the Lower-Middle Carboniferous boundary was taken at about the base of the Yeadonian Stage in the European scheme (later lowered to the base of the Kinderscoutian Stage), and the Middle–Upper boundary somewhere in the Cantabrian Stage (see various papers in Wagner *et al.,* 1979 that review this subject).

The concept of Upper Carboniferous used in this volume follows essentially that of Lane *et al.* (1985b). This grew out of an attempt to establish the first stratigraphical boundary in the Carboniferous that could be recognized throughout the world, and which has become known as the Mid-Carboniferous Boundary. It is placed just above the base of the Chokierian Stage in the European classification. For convenience, the base of the Chokierian is used in this volume as an approximation to the lower limit of the subsystem.

The top of the Upper Carboniferous has been the subject of almost as many problems as the base. In Europe, it is generally taken to be at the junction between the Stephanian C and Autunian stages, although how this fits in with the marine sequences in Russia, where the base of the Permian is normally defined, is far from clear (see papers in Meyen, 1980 for a review). However, as the matter does not directly impinge on any of the sites dealt with in this review, the subject will not be further discussed here.

Geological literature

In each of the chapters in this volume, a brief account of the literature relevant to that particular area will be given. This clearly obviates a major general review of the literature dealing with the British Upper Carboniferous. However, it is perhaps worthwhile briefly mentioning some of the more general accounts which provide a good introduction to the subject in its wider, national context.

Nineteenth century volumes such as that by Hull (1861) provide a most valuable review of the then available information on the coalfields. During the first part of the 20th century, two of the best accounts were by Allan (1928) and Bisat (1928), in papers presented to the first International Carboniferous Congress. A little while later, Trueman (1954) produced a wide-ranging review of the geology of the British coalfields, which summarized much of our knowledge at about the time of the Second World War. A major event in Britain was the holding in Sheffield in 1967 of the 6th International Carboniferous Congress, and the published proceedings include many papers dealing with this country; those by Ramsbottom (1969b) and Calver (1969a) are particularly helpful reviews. For the most up-to-date information on the Carboniferous geology of this country, reference may be made to Ramsbottom *et al.* (1978), Besly and Kelling (1988), Leeder (1988) and Guion *in* Cope *et al.* (1992).

Geological setting

The Upper Carboniferous of Britain was formed in an elongate belt of deposition lying between Poland and Ireland, that marks the contact-zone between the Gondwana and Laurasia continental plates (Besly, 1988). Originally separated by deep ocean (the Proto-Tethys of Leeder, 1988), the Gondwana plate progressively drifted north relative to the Laurasia plate during the Late Palaeozoic. By the Late Carboniferous, the deep ocean had totally disappeared, and eventually the collision caused significant uplift and deformation of the Laurasian foreland. This tectonic episode is termed the Variscan (or Hercynian) Orogeny. However, between the times of ocean closure and basin inversion, a complex set of localized, synorogenic basins developed on the foreland.

Exactly how these basins were generated has been the subject of several recent papers, which have postulated sometimes contrasting models. There are four main mechanisms that have been proposed, which may be summarized as (1) the northwards subduction of Gondwana under Laurasia, (2) transtension due to east–west mega-shear along the Gondwana–Laurasia plate boundary, (3) nappe loading due to the northwards migration of the Variscan front, and (4) north–south rifting and ocean spread due to the opening of a Proto-Atlantic'.

The ocean subduction model essentially grew out of the classic work of Kossmatt (1927), with his tectonic zonation of Europe. Recently, its most persuasive proponent has been Leeder (1982, 1988; see also Leeder and McMahon, 1988), who has invoked the McKenzie (1978) general crustal extension theory to explain certain details of the basin configuration. The Laurasian foreland, which he interprets as overlying a northwards-dipping subduction zone, is first subject to lithospheric extension and thinning during the Viséan and Early Namurian, due to back-arch tension. This is then followed by subsidence and basin-formation due to thermal sagging.

Dewey (1982) and Johnson (1982) also used the extensional theory to explain basin-development in the Late Carboniferous synorogenic belt. However, they argued that other tectonic processes were also in play at the time, most significantly the transtensional effects of lateral movement between the plates. The characteristic strike-slip faulting associated with transtension has been identified, particularly in the Midland Valley of Scotland (Read, 1988). The model was further developed by Higgs (1986), who postulated large-scale dextral shear along a fault in southern Britain. This was used to explain some of the problems of sediment provenance in the Culm and South Wales basins, but the view has not met with widespread acceptance.

Dewey (1982) also used nappe loading as a mechanism for basin development in the Late Carboniferous of Britain. Kelling (1988) in particular has explained features of the South Wales Coalfield, in terms of loading from nappes produced by a northwards migrating Variscan Front (see Chapter 4), such as the southerly source of much of the sediment. It would appear, however, that such effects were only significant in southern Britain, south of the Wales–Brabant Barrier.

All of the above models can probably be incorporated into a unified scheme for explaining various features of British Upper Carboniferous geology. However, there is another model which is radically different, and which has been most clearly expounded by Haszeldine (1984b, 1988). This invokes an east–west stress regime, due to the opening up of a 'Proto-Atlantic', and which is claimed to have produced an underlying north–south orientation to the basin configuration of northern Europe. Leeder (1988) has critically reviewed much of the evidence used to support this model, and found many difficulties. For instance, the evidence for a north–south trend in basin orientation is not clear, and the model also requires large-scale igneous activity for which there is little evidence. It is also difficult to incorporate into such a model the basin inversion and uplift that occurred towards the end of the Carboniferous. On the other hand, the other models that have been advanced are far from proved, and do not explain the offshore evidence which would seem to give some credence to the 'Proto-Atlantic' Model.

Whatever the mechanism(s) driving the sedimentary processes in Britain during the Late Carboniferous, the result has been five discrete areas of deposition, separated by areas of non-deposition and sometimes erosion (Guion *in* Cope *et al.,* 1992). These are, from south to north, Sabrina, the Wales–Brabant Barrier and the Southern Uplands Massif (Figure 1.1).

- The Culm Trough in south-west England. This was a shallow marine basin that was progressively filled during the Namurian by northerly derived deltaic sediments. Basin inversion and tectonic deformation here was rather earlier than in the rest of Britain, probably sometime in the middle Westphalian.
- The Kent Coalfield, which is effectively a western extension of the Franco-Belgian Basin. This coalfield is known only through boreholes and underground mine workings. As there is no exposure it will not be dealt with further here.

- The area immediately south of the Wales–Brabant Barrier, including principally South Wales, the Forest of Dean and the Bristol–Somerset coalfields. Like the Culm Trough, the Namurian is characterized by the progressive infill of a shallow marine basin by deltaic sediment, although it seems to have been 'less marine' than the Culm deposits. During the early and middle Westphalian (up to the middle Bolsovian), deposition was characteristically in a fluvio-deltaic regime, with extensive peat deposits. In the late Westphalian, however, uplift mainly to the south resulted in the influx of mainly arenaceous fluvial deposits (the Pennant formations).
- The area between the Wales–Brabant Barrier and the Southern Uplands Massif, and including the northern English Midlands, the Pennines, and northern England. Again, the Namurian is characterized by mainly northerly-derived deltaic deposits filling a shallow marine basin, and the lower and middle Westphalian by fluvio-deltaic deposition. Unlike further south, however, there is no evidence of major fluvial deposits in the late Westphalian, except in the southern margins of the area. Instead, the progressive development of Variscan movement resulted in the formation of red beds such as the Etruria Formation.
- The Midland Valley of Scotland. The general facies development here is similar to the area south of the Southern Uplands Massif, with predominantly arenaceous deposits in the Namurian, coal-bearing deposits in the lower Westphalian and red beds in the upper Westphalian. However, marine influence was significantly reduced, with the result that marine bands are fewer and less well developed. Also volcanicity was a much greater influence, both as an influence on basin configuration, and on sedimentation itself (e.g. the Ayrshire Bauxitic Clay Formation).

Chronostratigraphy

Throughout this volume, the regional chronostratigraphy known as the Heerlen Classification has been used. The scheme is generally used throughout Europe (other than Russia and the Ukraine) and eastern Canada, at least when dealing with predominantly non-marine deposits. A review of the historical development of this classification can be found in Wagner (1974, 1989), Wagner and Winkler Prins (1991, 1993), and Chapter 2 of the present volume. The main features of this scheme are shown in (Figure 1.2).

Biostratigraphy

Five main groups of fossils have been used for biostratigraphical work in the British Upper Carboniferous: ammonoids (goniatites), conodonts, non-marine bivalves, miospores and plant macrofossils. The relationship between the biozones developed for these various fossil groups, and the Heerlen stages, is summarized in (Figure 1.3).

Ammonoids (goniatites)

Ammonoids (commonly referred to as goniatites) have been extensively used for biostratigraphy in the Upper Carboniferous of Britain, particularly in the Namurian. Their stratigraphical use was first developed here by Bisat in the first half of this century (e.g. Bisat, 1924, 1928; Bisat and Hudson, 1943), and it has been developed in recent years, particularly by Ramsbottom (1969b, 1971a, 1979a, 1979b). A useful review of the topic in an international setting is provided by Ramsbottom and Saunders (1984).

As with the Mesozoic ammonites, these fossils have considerable potential value for detailed stratigraphical resolution. However, they are restricted to particular facies, which sometimes limits the geographical range over which they can be used. For instance, the ammonoids found in the Westphalian marine bands in Britain are almost totally unknown from outside the paralic belt of coalfields in northern Europe. Nevertheless, within this belt of Upper Carboniferous deposits, they provide an extremely fine resolution of the marine strata, and have played a central role in establishing their stratigraphy.

As has often been the case in British studies on Carboniferous stratigraphy, the ammonoid-bearing strata are usually classified according to a composite bio/litho/chronostratigraphical scheme. The marine bands are defined lithostratigraphically as a particular rock body, but also biostratigraphically by their fossil content. The bands have then been used as the basis for defining the bases of chronozones and stages.

In the present report, a more rigorous separation of the three main strands of stratigraphy has been maintained, following the philosophy outlined by Hedberg (1976). The marine bands are named, often with reference to particular ammonoid taxa (e.g. Subcrenatum Marine Band, Bilinguis Marine Band). Their fossil content allows them to be assigned to biozones or biosubzones, broadly following the scheme outlined by Ramsbottom (1969b), and shown in (Figure 1.3). However, these zones are only applicable to the marine strata, and not to the intervening non-marine beds. No attempt is made to impose the zonal definitions onto a sedimentological cyclicity, in an attempt to elevate them into a chronostratigraphical framework (as proposed by Ramsbottom *et al,* 1962, 1978); as the underlying assumptions on which this was based are disputed (Holdsworth and Collinson, 1988).

As stated above, the use of ammonoids for intercontinental correlations is often limited. However, Ramsbottom and Saunders (1984) have proposed a set of 'genus-zones' (perhaps more rationally referred to as superzones), which provide a potential means of making such wider correlations. These are shown in (Figure 1.3) together with the more traditional set of zones and subzones.

Conodonts

The limitations of ammonoids for establishing intercontinental correlations of the British Upper Carboniferous marine strata has been partially overcome by the use of conodonts. These fossils have proved of considerable significance for establishing world-wide stratigraphical correlations of these strata, and have played a particularly important role in establishing the Mid-Carboniferous Boundary (Lane and Baesemann, 1982). In Britain, the seminal work has been by Higgins (1975, 1985), who proposed a biostratigraphy, which is summarized in (Figure 1.3).

Non-marine bivalves

While ammonoids have played the key role in establishing stratigraphical correlations in the Namurian in Britain, non-marine bivalves have tended to play the major role in the Westphalian. This reflects at least in part the less marine character of the Westphalian deposits in this country. Their use seems to have been triggered by Hind's (1894–1896, 1896–1905) monographs on these shells, and the earliest coherent biostratigraphy was published by Davies and Trueman (1927) and Dix and Trueman (1937). The most complete account of these fossils in Britain is the monograph by Trueman and Weir (1946–1968). Most recently, major progress has been made by Eagar in understanding the relation between the variation of these shells and environment (Eagar, 1947, 1952a, 1952b, 1953b, 1956, 1960, 1987). This has considerably improved the utility of these fossils as reliable biozonal indices. Together with studies by Wright *in* Tonks *et al.* (1931) and Calver (1956), Eagar's work has also helped develop subdivisions of the zones, which some have referred to as 'faunal belts', but which are clearly subzones.

There is no published account detailing the various bivalve zones and subzones currently used in Britain. The best summary is in the table given in Ramsbottom *et al.* (1978, plate 1), which lists the names and chronostratigraphical positions of the zones and subzones. This is used as the basis of the biostratigraphy shown here in (Figure 1.3). It should be emphasised that they are used here in an exclusively biostratigraphical sense, with no attempt to convert them into chronozones as effectively done by Calver (1969a).

Palynology

The potential value of palynology for geological investigation, particularly where borehole data are predominant, is that it requires only small rock samples to prepare many fossils. As a consequence, they have been much used in the Upper Carboniferous of this country, especially over the last quarter century or so. The first major contribution in the field was by Smith and Butterworth (1967), who established a biostratigraphy based on coal palynology, mainly from the British Westphalian, while Owens *et al.* (1977) produced the first coherent scheme for the Namurian. Other major contributions have been by Clayton *et al.* (1977) and Owens *et al.* (1978), and a useful review of the subject in an international setting is provided by Owens (1984).

Most Upper Carboniferous palynology has been based on spores, pre-pollen and pollen <200 μm in diameter. They are known as miospores, obviating the problem of using the term microspore, which implies that it is from a pteridophytic plant. Palynomorphs >200 µm in diameter, known as macrospores, also occur commonly in these strata, but have not been so widely used for biostratigraphy. The only significant exception has been the work by Spinner (1960) in the Forest of Dean.

The weakness of palynological work is that it cannot normally be done in areas where coalification ranks are high (according to Smith and Butterworth, 1967, coals with >90% carbon). In South Wales, for instance, most of the coals are anthracitic with typically 92% or higher carbon, and only in the far east of the area are ranks slightly lower, allowing the preservation of pollen and spores (Sullivan, 1962). There are also often taxonomic difficulties in interpreting such isolated pollen and spores, which have often been assessed with no reference to the parent plant and thus of natural morphological variation (Thomas, 1987). Consequently, the zonal boundaries tend to be 'fuzzy', being based on changes in proportions of taxa rather than by absolute ranges. Nevertheless, palynology has proved of value in parts of Britain, especially in the lower Westphalian of northern England.

Plant macrofossils

Although there were significant studies in this field in the first half of the 20th century (e.g. Kidston, 1905; Dix, 1934, 1937), more recently such fossils have not been widely favoured as biostratigraphical tools. It is generally considered that plants can give good indication of broad divisions and of general overseas correlations, but the ranges of individual species are usually too long to provide the finer divisions given by the bivalves (Ramsbottom *et al.,* 1978, p. 5). This is in fact quite misleading, except possibly in the Langsettian, as a comparison of the relative biostratigraphies for bivalves and plants, as shown in (Figure 1.3) will demonstrate. In fact, in the Westphalian D and Cantabrian of Britain, plant fossils are the only proven and reliable biostratigraphical indices (e.g. Cleal, 1978, 1984a, 1992).

The most robust set of plant biozones for these fossils was established by Wagner (1984). This has been refined by Cleal (1991), who has incorporated a number of subzones in the classification to improve the resolution of the scheme, as well as providing a general review of the topic.

Lithostratigraphy

Formations and groups

There is considerable variation in the lithostratigraphical development of the Upper Carboniferous of Britain, and different areas often have their own set of formations. Only what is called here the Productive Coal Formation (the mainly Westphalian, grey, coal-bearing deposits) has a reasonably wide distribution. Consequently, the definitions of the formations are dealt with separately in the relevant chapter for the area concerned.

However, there is an underlying pattern of litho-facies recognizable over much of the country, and this is recognized here as five groups listed as follows.

Culm Group

Character: predominantly marine or marginal non-marine deposits found in Culm Trough.

Component formations: Crackington, Bideford and Bude.

Yoredale Group

Character: marine shales and limestones found in northern England, mainly in the Lower Carboniferous, but sometimes just extending into the basal Upper Carboniferous.

Component formations: Whitehouse Limestone.

Millstone Grit Group

Character: mainly marine shales and deltaic sandstones found in the Namurian and basal Westphalian of England and Wales.

Component subdivisions: Basal Grit, Middle Shales, Farewell Rock and Bishopston for mations in South Wales; Holywell Shales, Gwespyr Sandstone, Cefn-y-fedw Sandstone, Lower Shales, Dee Bridge, Upper Shale and Aqueduct Grit formations in North Wales; Quartzitic Sandstone Formation in the Bristol area; Edale Shales, Kinderscout Grit, Middle Grit and Rough Rock subgroups in the Pennines; and First Grit and Second Grit formations in northern England.

Passage Group

Character: deltaic sandstones and volcanogenic deposits of the middle Namurian to basal Westphalian of Scotland.

Component formations: Ayrshire Bauxitic Clay and Roslin Sandstone.

Coal Measures Group

Character: grey and red measures, of mainly fluvio-deltaic origin, often including coal deposits, but with only thin marine beds.

Component formations: Productive Coal, Etruria, Halesowen, Newcastle, Keele, Enville, Whitehaven Sandstone and Barren Red.

Up to a point, this grouping of formations into groups is subjective. For instance, the separation of the Millstone Grit and Passage groups is arguable, and really follows more historical precedence than clear sedimentological difference. Also, the inclusion of red beds in the Coal Measures is a moot point, and they might perhaps be better placed in a group linked with the New Red Sandstone Supergroup. Nevertheless, it provides a set of terms that conveniently summarize the broad pattern of deposition during the Late Carboniferous in Britain, and thus has a role to play that is supplemental to that provided by the formational divisions.

Marker horizons

Most stratigraphical correlations in the British Upper Carboniferous are based on biostratigraphical criteria, as discussed above. However, there are two types of 'marker horizon' available in these strata that provide valuable, abiotic means of establishing time-planes.

The most widely used are the marine bands. During the Late Carboniferous, Britain saw a progressive change from predominantly marine to predominantly non-marine conditions, and the preserved sedimentary sequence can be interpreted in terms of the interplay between these two broad environments. Particularly in the upper Namurian to middle Westphalian (Yeadonian to Bolsovian) conditions were predominantly non-marine with only occasional, discrete marine incursions, and the resulting marine bands are very widespread. The bands have been identified throughout the paralic belt of coalfields from Ireland in the west (Eagar, 1975) to the Lublin Coalfield (Poland) in the east (Musia *et al.,* 1983), and the most widespread have been used to place the stage boundaries in their stratotypes (see Chapter 2). In Britain, the most significant contributions on the marine bands have been by Ramsbottom (1969b, 1971a, 1977, 1978, 1979a, 1979b) in the Namurian, and Calver (1968, 1969a) in the Westphalian. The stratigraphical positions of the marine bands are summarized in (Figure 1.4).

The second type of 'marker horizons' consists of cineritic tonsteins, which were the result of volcanic ash-falls. They have proved particularly important for establishing correlations between the paralic coalfields and the intra-montane basins, such as Saar–Lorraine, where marine bands do not occur (e.g. Bouroz, 1967). In Britain, they have not been as widely investigated as in continental Europe (although see Burger, 1985 for a review of the available information and its potential significance in Britain, particularly in the Bolsovian). However, the radiometric results from Germany by Lippolt *et al.* (1984) have a direct relevance to the British stratigraphy, as they provide the first reasonably accurate, absolute chronology for these strata (reviewed by Leeder, 1988).

Geochronology

For most purposes, geologists tend not to use absolute ages in their stratigraphical work. Radiometric geochronology is still a relatively inexact science and cannot come anywhere near the resolution of more traditional stratigraphical tools such as biostratigraphy. It is nevertheless helpful to give some sort of idea as to the approximate age of strata, especially for the non-specialist reader, and this has been done in the 'Conclusions' section of each site report.

For many years, the geochronological data summarized by Harland *et al.* (1982) were the standard in this field, but these had only a relatively few calibration points in the Late Carboniferous. The position improved dramatically with the work of Lippolt *et al.* (1984) and Lippolt and Hess (1985) on sanidine crystals from tonsteins. Their results may be summarized as follows: 'Late Namurian A' (probably Chokierian) — 319.5–324.8 Ma; latest Duckmantian — 310.7 Ma; middle Bolsovian 309.5–310.7 Ma; late Barruelian — 302.9 Ma; Stephanian C — 300.3 Ma. Using these calibration points, Leeder (1988) estimated that the Namurian represented 11 million years, the Westphalian 10 million years, and the Stephanian 5 million years. The start of the Late Carboniferous (i.e. Chokierian Era) is thus about 320 Ma, and the end of the Late Carboniferous about 300 Ma.

Although these results seem reasonable, they have recently been questioned by Riley *et al.* (in press), who have obtained dates of about 314 Ma from two separate marine bands in the middle Arnsbergian (i.e. just below the Mid-Carboniferous boundary). If correct, this would clearly have a major impact on our understanding of Late Carboniferous chronology; the lower half of the Westphalian and most of the Namurian would have to be telescoped into just 4 million years, which is less than the time that the Bolsovian and Westphalian D alone are currently thought to represent (i.e. 5 million years). It must be suspected that either this new Arnsbergian date is wrong, or at least some of the Lippolt and Hess dates are wrong. Either way, it underlines the difficulties inherent with radiometric dating. In this volume, the Lippolt and Hess dates have been retained, but these may have to be revised when further radiometric evidence becomes available.

British sites in an international context

Before embarking on the detailed analysis of the significance of the British Upper Carboniferous sites, it is perhaps worthwhile outlining where the most obvious comparisons are likely to be found.

The strong climatic zonation of the world during the Late Carboniferous, as evidenced by the palaeobotanical data (Cleal and Thomas *in* Cleal, 1991), effectively restricts any comparison to the palaeoequatorial belt (Figure 1.5), i.e. North America, Europe, northwest Africa and China. Most of Gondwana has relatively little Upper Carboniferous, and what there is shows a strong glacial influence, which is markedly different from anything found in Britain (Wagner *et al.,* 1985). In the northern palaeolatitudes, in Angara, conditions were not so drastically different, with some coal-bearing strata developing (Rotay, 1975). However, both faunas and floras were quite different from those of the palaeoequatorial belt, and the biostratigraphy of the deposits are thus totally dissimilar; to all intents and purposes, sequences in these two regions are still uncorrelatable.

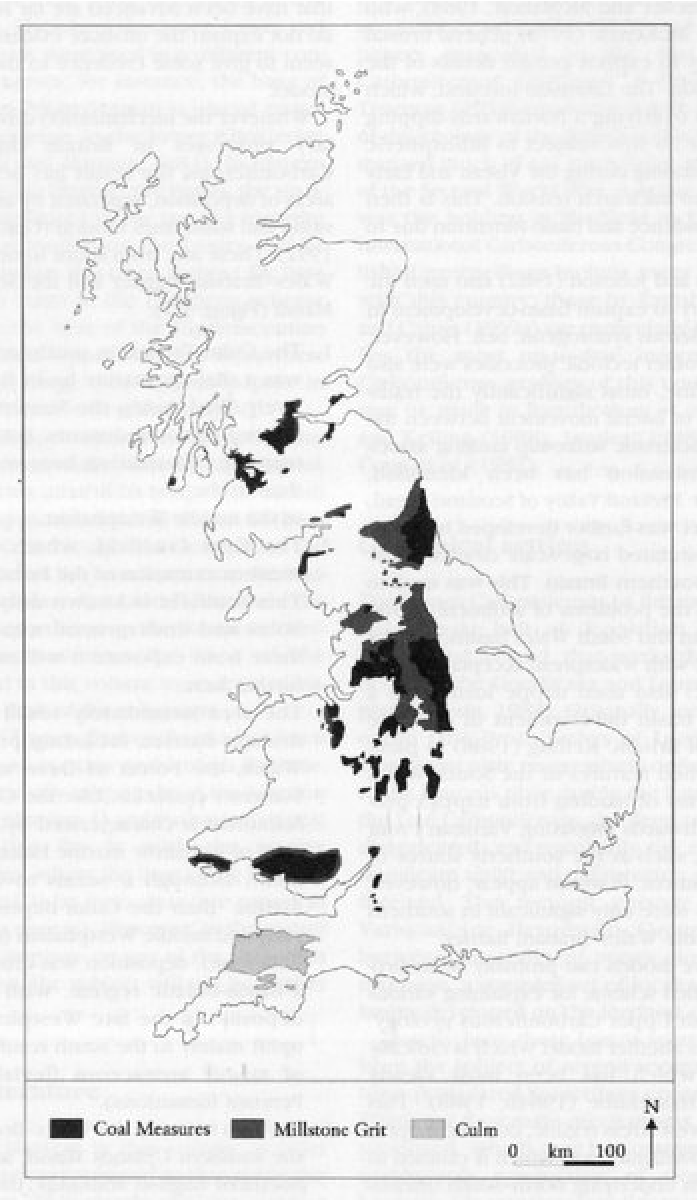
Within the palaeoequatorial belt, the most obvious comparisons are with the sequences within what is termed the paralic belt, in northwestern and central Europe. These include the deposits of the Franco-Belgian Basin, Limburg, the Ruhr and the Lublin area of Poland. In few cases, however, are these strata well exposed. Thus, although comparisons are possible based on data determined from boreholes or underground workings, it is rarely possible to make comparisons based on surface outcrops. The belt of coalfields also probably extends into easternmost North America, in particular the Maritime Provinces of Canada. Here, there are good exposures, particularly of the upper Westphalian and lowermost Stephanian, which rival and in some cases better the British sites. However, the position in the Namurian and lower Westphalian is nowhere near as good as in Britain.

In the rest of the palaeoequatorial belt, areas tend to fall into two broad categories. The one that offers the closest comparison with the British sites includes the intramontane basins, particularly of central Europe, such as Saar–Lorraine and the Intra-Sudetic Basin. These include coal-bearing sequences, which offer some comparison, especially with the upper Westphalian parts of the British successions. However, both faunally and florally, they differ from the British sites (e.g. Gothan, 1951, 1954). There are also significant differences from a sedimentological standpoint, with the intramontane sequences representing mainly large-scale lacustrine deposits (Kneuper, 1970; Holub, 1977).

The second category are those areas where marine conditions either occur exclusively (e.g. South China, Urals, Moscow Basin) or predominantly (e.g. Appalachians, northern Spain, North China, Ukraine) (Englund *et al.,* 1979; Wagner *et al.,* 1979, 1983; Martinez Diaz, 1983). The presence of shelf limestones immediately distinguish these areas from the Upper Carboniferous as seen in Britain. In many of these areas, non-marine conditions become significantly less evident higher in the Upper Carboniferous, and in some cases (e.g. northern Spain) effectively disappear in the upper Stephanian. However, in all of these cases, the Westphalian strata are predominantly marine, and thus quite different from the coeval deposits in Britain.

To conclude, Britain offers a unique opportunity to examine Namurian to basal Stephanian deposits in a primarily terrigenous, fluvio-deltaic setting. Comparable successions can only be found in parts of northwestern and central Europe, and only in Britain is there an extensive suite of exposed and conservable sites.

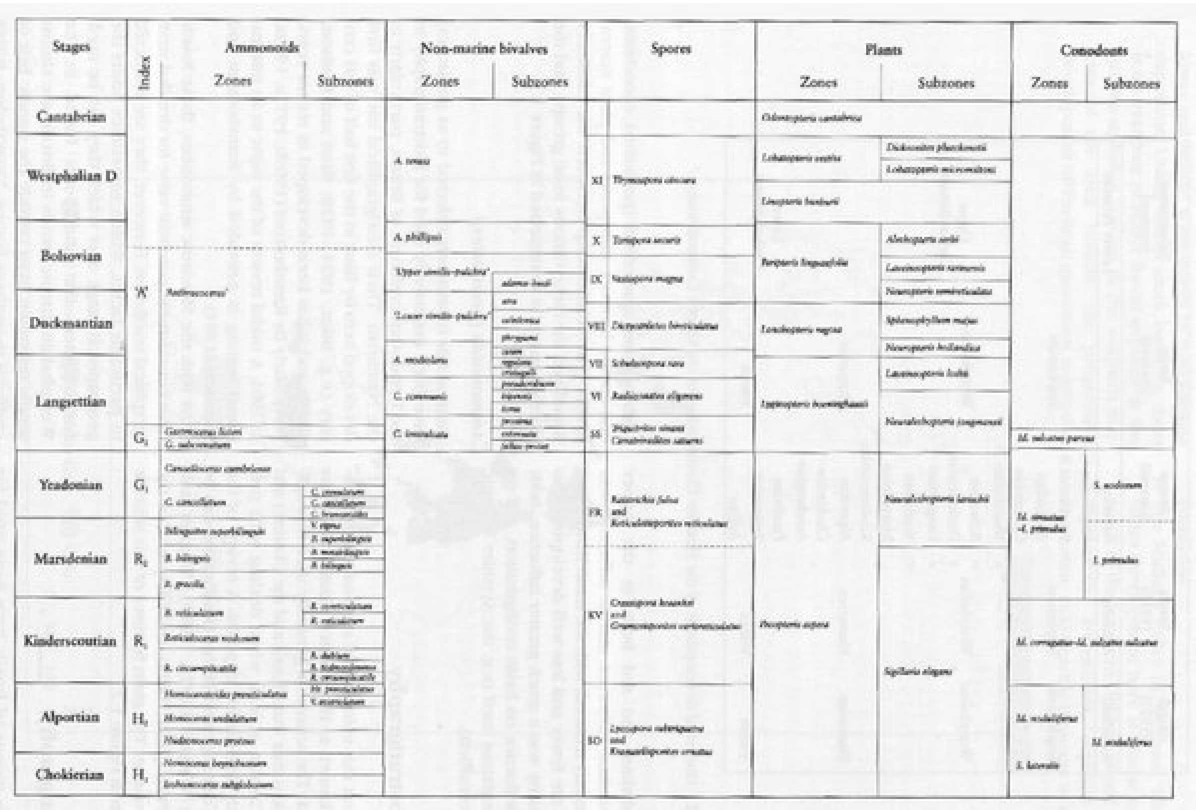
References



(Figure 1.1) Main outcrops of Upper Carboniferous sedimentary rocks in Britain. Adapted from maps in Duff and Smith (1992), and Macgregor and Macgregor (1966).

Stages (1927)	Stages (1935)	Stages (current)	Series (current)	Subsystems (current)
Autunian	Autunian	Autunian		Lower Permian
Stephanian	Stephanian	Stephanian C	Stephanian	Upper Carboniferous
		Stephanian B		
		Barruelian		
? ? ?	? ? ?	Cantabrian		
Westphalian	Westphalian D	Westphalian D	Westphalian	
C	C	Bolsovian		
B	B	Duckmantian		
A	A	Langsettian		
Namurian	Namurian C	Yeadonian	Namurian	
	B	Marsdenian		
		Kinderscoutian		
		Alportian		
	A	Chokierian		
		Arnsbergian		Lower Carboniferous
		Pendleian		
Visean	Visean	Brigantian	Visean	
		Asbian		

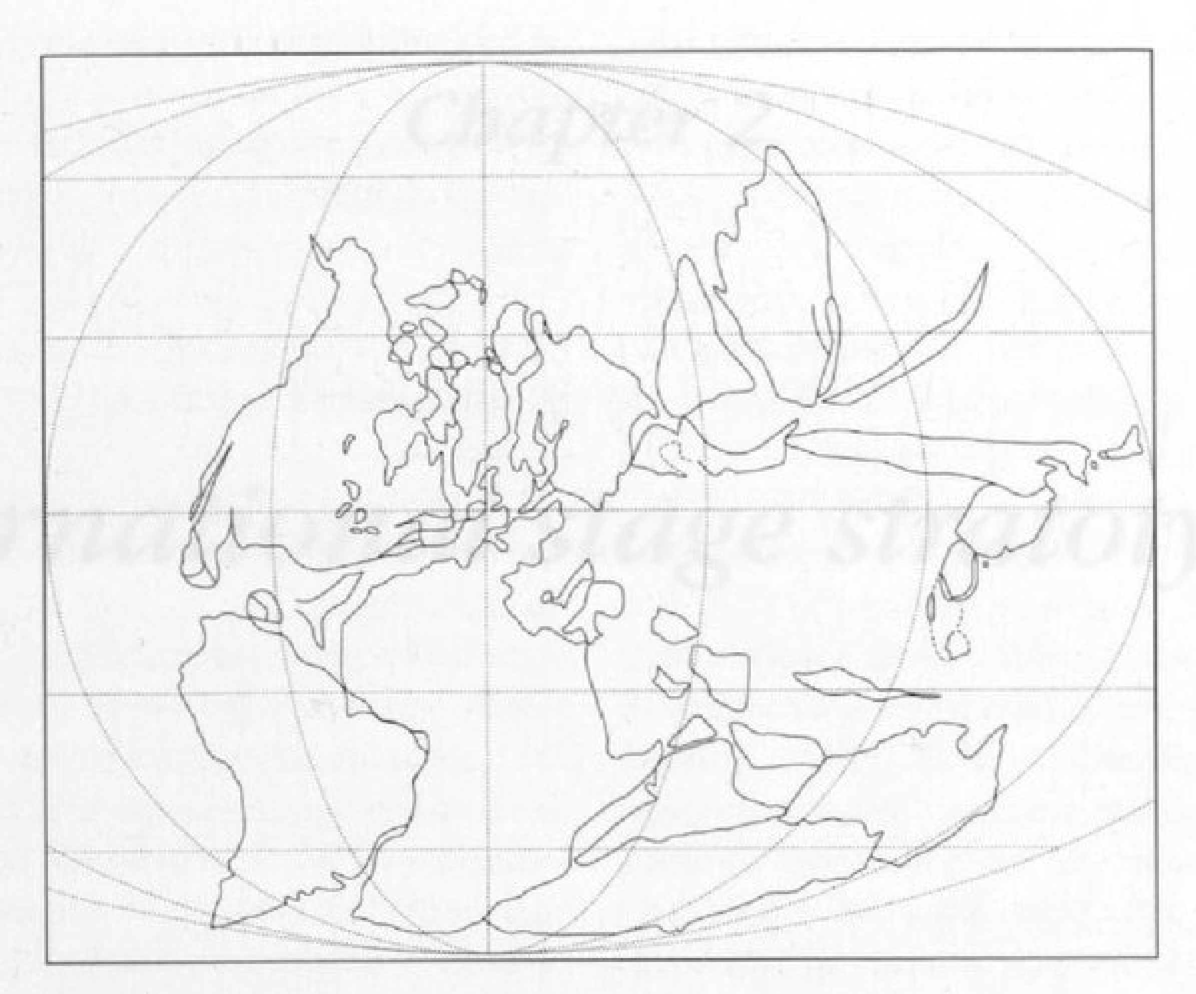
(Figure 1.2) Historical development of the Heerlen Classification of the Upper Carboniferous.



(Figure 1.3) The relationship between the stages of the Heerlen Classification and the biozones established for the most useful fossil groups in the Upper Carboniferous of Britain.

Series	Stage	Marine band
Westphalian (part)	Bolsovian	*gap* Cambriense Shafton Edmondia Aegiranum
	Duckmantian	Haughton Clown Maltby *gap* Vanderbeckei
	Langsettian	*gap* Burton Joyce Langley Amaliae Meadowfarm Parkhouse Listeri Honley Springwood Holbrook Subcrenatum
Namurian (part)	Yeadonian	Cumbriense Cancellatum
	Marsdenian	Sigma Superbilinguis Metabilinguis Eometabilinguis Bilinguis (3) Bilinguis (2) Bilinguis (1) Gracilis
	Kinderscoutian	Coreticulatum Reticulatum (3) Reticulatum (2) Reticulatum (1) Stubblefieldi Nodosum Eoreticulatum Dubium Todmordenense Subreticulatum Circumplicatile Magistrorum
	Alportian	Prereticulatus Eostriolatus Undulatum Proteus
	Chokierian	Isohomoceras Beyrichianum Subglobosum (3) Subglobosum (2) Subglobosum (1)

(Figure 1.4) The chronostratigraphical positions of the main marine bands in the Westphalian of Britain.



(Figure 1.5) Late Carboniferous palaeogeography after Scotese (1986; modified from Laveine et al., 1993), showing the position of the palaeoequatorial belt.