Chapter 2 Midland Valley Basin

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Introduction

Lower Carboniferous rocks in Scotland are largely confined to the Midland Valley of Scotland, within which they have a wide and complex outcrop (Figure 2.1). This NE–SW-trending region is over 250 km long and about 80 km wide. It is bounded to the north by the Highland Boundary Fault, which separates it from the Dalradian rocks of the southern Grampian Mountains. To the south it is separated from the Ordovician and Silurian rocks of the Southern Uplands by a series of faults related to, and including, the Southern Uplands Fault. Although relatively low when compared to the areas to the north and south, the Midland Valley is not a simple lowland tract but a complex of lowland and more upland areas reaching up to about 700 m above sea level. This landscape has had a complex history of development and, though it is often mantled by a variable thickness of Quaternary deposits (Sissons, 1967, 1976), the topography is frequently broadly controlled by the underlying bedrock geology. In particular the presence of igneous extrusive and intrusive rocks explains many of the more extensive upland tracts, such as the Campsie and Touch Hills or the Bathgate Hills, as well as the more isolated hills, such as the East and West Lomond Hills or Arthur's Seat.

The geology of the Midland Valley is structurally complex and the present disposition of Carboniferous rocks reflects in large part the pattern of depositional basins that evolved during the Carboniferous Period. At the centre of these basins, which often form more lowland ground, are outcrops of Upper Carboniferous rocks including the productive Coal Measures Group (Figure 2.1). Lower Carboniferous rocks crop out round the peripheries of the basins or in the intervening areas between basins. The principal basinal areas are the Ayrshire Basin, the Central Coalfield Basin, the Stirling–Clackmannan (Kincardine) Basin, the Midlothian Basin and the Fife Basin. Smaller basins occur in the Douglas and Muirkirk areas. Lower Carboniferous rocks also crop out in elongate basins within the Southern Uplands. The Oldhamstocks Basin and the Sanquhar–Thornhill Basin are the most important of these NNW–SSE-trending areas. Outcrops of Lower Carboniferous rocks to the north of the Firth of Tay (Browne, 1980a), the Macrahanish and other isolated small outcrops within the southern Grampians (Stephenson and Gould, 1995) indicate that the Lower Carboniferous succession once had a greater northerly extent, particularly at the western end of the Midland Valley (George, 1960). To the east it connects offshore with the Forth Approaches Basin (Gatliff *et al.,* 1994) and to the west it connects with basins in the Clyde and in Northern Ireland (McLean and Deegan, 1978).

History of research

The Lower Carboniferous rocks of the Midland Valley have in the past provided a great diversity of economic resources and it is clear that the rocks were in many places known 'long ere geology had arisen to give them a definite name and to recognize their stratigraphical position' (Geikie, 1902). The early accounts of sites and of Carboniferous geology are often linked to the exploitation of limestone or coal (e.g. Langdale, 1835, 1837; Carmichael, 1837). Records in the Statistical Accounts (e.g. Sherrif, 1796) also reflect this but show too that early workers had begun to take a more general interest in Lower Carboniferous geology and palaeontology. As pointed out and summarized by Geikie (1902), some of the early workers were involved in the controversies of the day and used evidence from Lower Carboniferous rocks in their accounts. Other notable accounts include MacLaren's (1839) summary of the *Geology of Fife and the Lothians, in* which the stratigraphical term 'Calciferous Sandstone' was first used, and Brown's (1860) logged sections on the coast of Fife. At the same time, workers such as Craig (1839), Montgomery (1839), Bryce (1855) and Young (1860) were taking an interest in and describing outcrops at the western end of the Midland Valley.

The fossil content of the strata was of particular interest to a number of early workers, who laid down the foundations for future generations of Carboniferous palaeontologists (Clarkson, 1985). The efforts of two of the foremost early workers, the Reverend David Ure (Ure, 1793) and the Reverend John Fleming (Fleming, 1828), are permanently linked in the names of such typical Lower Carboniferous fossils as *Archaeocidaris urii* Fleming, *Euphemites urii* (Fleming) and *Crurithyris urii* (Fleming). Hibbert's (1836) study of the Burdiehouse Limestone is particularly outstanding not only for the way in which he marshalled the palaeontological evidence to show that it was a freshwater deposit but also for recognizing its broad stratigraphical position within the Midlothian Basin and for providing a succession of the stratigraphically higher Loanhead Coals (Limestone Coal Formation). Later significant studies on Scottish Carboniferous palaeontology include work by Kirkby (Jones and Kirkby, 1867; Jones *et al.,* 1874–1884) on ostracodes, Thomson (e.g. 1874, 1880, 1883, 1887) on corals, Davidson (1851–1886, 1860) on brachiopods, the Youngs (Young and Young, 1874a,b, 1876; Young, 1885a,b, 1895) on bryozoans, and Hind (1896–1905) on bivalves. Young (1866) made some interesting observations on the distribution of *Lingula,* and Neilson (1895), who wrote that he wished to 'read the life story of the fossils and from it deduce the conditions under which the strata containing them they were laid down', also recognized the stratigraphical usefulness of the fauna above the Blackhall Limestone (Lower Limestone Formation), which now bears his name (Neilson, 1874, 1913). The distribution of fossils in the west of the Midland Valley was summarized in Young and Armstrong (1871) and revised by Armstrong *et al.* (1876). Other significant local and stratigraphical studies include Craig (1867, 1869, 1875, 1879, 1883), McPhail (1869), Kirkby (1880, 1901) and Smith (1882).

It was, however, with the work of the [British] Geological Survey, commencing in the 1850s, that understanding of the Scottish Lower Carboniferous succession and its stratigraphy began to gain greater coherence. In addition to published maps, a number of memoirs were produced, of which those on Central and West Fife (Geikie, 1900), East Fife (Geikie, 1902) and Edinburgh (Peach *et al.,* 1910) are particularly outstanding; the East Lothian (Clough *et al.,* 1910) and Glasgow (Macgregor *et al.,* 1925) memoirs are also significant. The economic development of the West Lothian Oil Field starting in the latter part of the 19th century provided a focus for survey work in this area culminating in the definitive oil shale memoir (Carruthers *et al.,* 1927). Further impetus had been given to this work by the economic demands created by the First World War and these hostilities also emphasized the significance of the Scottish coalfields, including reserves in the Limestone Coal Formation. An extensive and protracted revision of the coalfield regions was undertaken and ultimately resulted in a series of economic memoirs, on not only the Central Coalfield, but also the Stirling–Clackmannan, Fife, Midlothian and Ayrshire coalfields (see list in Macgregor and MacGregor, 1967), all of which included chapters on the Lower Carboniferous rocks. Some relevant sheet memoirs were also produced during this period (Tyrrell, 1928; Richey *et al.,* 1930; Eyles *et al.,* 1949) and subsequently (Francis *et al.,* 1970, Forsyth and Chisholm, 1977; Armstrong *et al.,* 1985; McAdam and Tulloch, 1985; Davies *et al.,* 1986; Greig, 1988). In addition, officers of the [British] Geological Survey published valuable accounts of aspects of Scottish Lower Carboniferous geology both in other survey publications (e.g. Dinham, 1920; Richey, 1937; Goodlet, 1957; Lumsden, 1964, 1967a,b; Forsyth and Wilson, 1965; Wilson, 1966, 1974; Davies, 1972; Browne, 1980a; Paterson and Hall, 1986), and in scientific journals (e.g. Crampton, 1905; Carruthers and Anderson, 1908; Carruthers and Richey, 1915; Richey, 1925, 1946; Macgregor, 1930; Macgregor and Manson, 1935; Goodlet, 1959; Read, 1965; Read and Merriam, 1966; Read and Johnson, 1967; Chisholm and Dean, 1974; Browne, 1980b; Monro, 1982a; Browne and Monro, 1989; Chisholm and Brand, 1994). The prolific Etheridge (e.g. 1873, 1875, 1876, 1878, 1880, 1882) published on a wide range of Lower Carboniferous fossils, and Carruthers' (1910) study of variation in zaphrentids has become a textbook example (Clarkson, 1998). Other important works on Scottish Lower Carboniferous palaeontology include Wilson (1979, 1989), Brand (1970, 1972, 1998) and Graham (1970, 1972, 1988).

At the same time, other workers have also made significant contributions to understanding and debate about successions, including Macnair (1906, 1915, 1916, 1917), Craig and Balsillie (1912), Macnair and Conacher (1913, 1914), Kirk (1925) and Cumming (1928). Study of microfloras (Burgess, 1965; Sullivan, 1968; Clayton, 1971, 1985; Neves *et al.,* 1973) opened up an important new biostratigraphical field. Research on faunas includes Weir (1931) on bellerophontids, Latham (1932) on ostracodes, Hill (1938–1941) on corals, Currie (1954) on goniatites, Clark (1960) and Dean (1987) on conodonts, and Bancroft (1985a,b, 1986a) on bryozoans, while Wright's passion for crinoids is summarized in his two major monographs (Wright, 1939, 1950–1960). The value of detailed palaeoecological work was shown by the seminal studies of Craig (1954) and Ferguson (1962, 1963), and the work of Shiells (1966, 1968, 1969; Shiells and Penn, 1971) on productoid brachiopods combined taxonomy with functional morphology. Combinations of palaeoecology and sedimentology were important in recent studies of carbonates (Cain, 1968; Jameson, 1987; Pickard, 1990, 1992, 1993, 1994) and modern sedimentological insights have led to re-interpretations of a number of sections (Greensmith, 1965; Belt *et al.,* 1967; Browne, 1975; Loftus, 1984; Maddox and Andrews, 1987; Fielding *et al.,* 1988;Loftus and Greensmith, 1988; Searl and Fallick, 1990; Andrews *et al.,* 1991; Andrews and Nabi, 1994, 1998).

The most recent tranche of survey memoirs (Paterson *et al.,* 1990, 1998; Forsyth *et al.,* 1996; Cameron *et al.,* 1998; Hall *et al.,* 1998; Monro, 1999), some of which deal with areas last covered by sheet memoirs of the 1870s (Whyte, 2000), have provided important regional syntheses and an evolving understanding of the Mid-Dinantian Break. They also embody important changes in stratigraphical nomenclature and usage, which have been further reviewed and revised by Browne *et al.* (1999).

Cameron and Stephenson (1985) and Francis (in Craig, 1965, 1983, 1991) have provided useful overviews of the Scottish Carboniferous System and useful bibliographies can be found in Gelkie (1900, 1902), Peach and Horne (1903), Macgregor *et al.* (1925) and Richey *et al.* (1930).

Stratigraphy

The Lower Carboniferous lithostratigraphy of the Midland Valley (Figure 2.2) has developed independently of other areas within the British Isles. This is a consequence both of its separation from other areas and of its markedly different succession. Because of the internal complexity of the region its stratigraphy also developed and evolved in a piecemeal fashion, with considerable debate over the detailed correlation from one area to another.

In broad terms it has become widely recognized that a lower unit, called the Calciferous Sandstone Series, could be distinguished from an upper unit, the Carboniferous Limestone Series, in which the Upper Limestone Group and Lower Limestone Group were separated by a suite of coal-bearing strata. These latter rocks were at first sometimes referred to as the 'Lower Coal Measures' to distinguish them from the Coal Measures of the Upper Carboniferous succession. They were also know by different names in different basins, for example the 'Edge Coals' of Midlothian, but became generally termed the 'Limestone Coal Group'. As summarized by Macgregor (1930), the boundaries of the upper three units were defined by marker horizons, which could generally be traced throughout the outcrop. Thus, for instance, the top of the Lower Limestone Group was defined by the top of the Top Hosie Limestone, whereas its base was defined by the base of the Hurlet Limestone. Similarly the top of the Upper Limestone Group was defined by the top of the Castlecary Limestone, while its base was defined by the base of the Index Limestone. The Limestone Coal Group was thus defined as the strata from the top of the Top Hosie Limestone to the base of the Index Limestone. The usage of these divisions on [British] Geological Survey maps was re-affirmed by MacGregor (1960), while the term 'Calciferous Sandstone Measures' was introduced for the lowest unit. The great lithological variation seen within the Calciferous Sandstone Measures and the common presence of thick volcanic units inhibited any region-wide subdivision of this unit though local stratigraphies were developed for different regions (see summaries in Macgregor, 1930; Francis in Craig, 1965; Macgregor and MacGregor, 1967).

More recently, a progressive series of changes (Chisholm *et* ed., 1989; Chisholm and Brand, 1994; Browne *et al.,* 1996), which have been reviewed and clarified by Browne *et al.* (1999), have been introduced to bring the lithostratigraphical nomenclature into line with modern practice. The upper three groups have been reclassified as formations, which pleasingly otherwise retain their traditional names, and are united with the Upper Carboniferous Passage Formation in the Clackmannan Group (Browne *et al.,* 1999) (Figure 2.2). The term 'Calciferous Sandstone Measures' has, however, been discontinued and replaced by two units; an upper Strathclyde Group and a lower Inverclyde Group (Paterson and Hall, 1986; Browne *et al.,* 1999). Initially introduced in the west of Scotland (Paterson and Hall, 1986), it is now recognized that these two groups can be distinguished throughout the Midland Valley (Browne *et al.,* 1999) (Figure 2.2).

Following Paterson and Hall (1986), the Inverclyde Group is subdivided into three formations, the Kinnesswood Formation, Ballagan Formation and Clyde Sandstone Formation (Figure 2.2), which can be widely recognized across the Midland Valley (Browne *et al.,* 1999). The lowest of these, the Kinnesswood Formation, was formerly known as the 'Cornstone Beds' and was usually included within the Upper Old Red Sandstone (Paterson and Hall, 1986; Browne *et al.,* 1999). However, the Clyde Sandstone Formation also includes cornstone horizons and the association of these two cornstone-bearing formations along with the cementstone-bearing Ballagan Formation in the Inverclyde Group was considered to be lithologically more coherent than previous practice (Paterson and Hall, 1986). The remaining parts of the Upper Old Red Sandstone have been placed in another major new group, the Stratheden Group (Paterson and Hall, 1986). Note that the term 'cornstone' has traditionally been used to describe nodular developments of calcium carbonate within clastic intervals. However, these developments are widely regarded as the product of pedogenic processes (Allen,

1974) and are subsequently referred to in this chapter as 'calcretes'. Two other terms, 'cementstone' and 'fireclay', have been retained in this chapter because of their special meaning. The lithological term 'cementstone' refers to argillaceous limestone and dolostone, whereas the term 'fireclay' refers to a poorly bedded mudstone high in alumina (Craig, 1991). Most fireclays are seatearths (palaeosols) below coals, but some are not associated with coal and do not contain roots (Craig, 1991).

The subdivision of the Strathclyde Group into a number of sedimentary and volcanic formations of more local extent, and in some cases with markedly diachronous boundaries, has also been formalized (Browne *et al.,* 1999) (Figure 2.2). In addition, the Bathgate Group —comprising the Salsburgh Volcanic Formation, the Bathgate Hills Volcanic Formation and the Kinghorn Volcanic Formation — has been defined for the extrusive rocks of West Lothian and West Fife (Browne *et al.,* 1999). These interdigitate with strata of the Lawmuir Formation, Lower Limestone Formation, Limestone Coal Formation and Upper Limestone Formation and extend up to interfinger with the Passage Formation.

The chronostratigraphy and biostratigraphy of the Scottish Lower Carboniferous succession has been particularly difficult and it is only comparatively recently that major progress has been made. This is because good marine faunas are lacking in the lower parts of the sequence, and even in the upper parts of the sequence where they do occur, marine faunas are intermittent and interbedded with non-marine strata. It was thus virtually impossible to apply the classic coral–brachiopod zonations (Hill, 1938–1941; Francis in Craig, 1965) and, though Currie (1954) on the basis of a very patchy and fragmentary record was able to recognize goniatites indicative of B, P_1, P_2 and E biozones, only the $P_{2–E1}$ boundary could be approximated as lying close to the top of the Lower Limestone Formation. The development of a zonal scheme based on miospores (Neves *et al.,* 1973; Clayton, 1985) has, however, provided a basis for correlation both within the Midland Valley and with Carboniferous outcrops elsewhere. Many of the original concurrent range zones were first recognized and defined using material from the Spilmersford Borehole in East Lothian. The linking of the miospore zones with chronostratigraphical stages (George *et al.,* 1976; Riley, 1993; Browne *et al.,* 1999) means that these stages can now be more reliably recognized and meaningfully used within the area (Figure 2.2) though the boundary positions both of zones and stages remain very uncertain.

The recognition of the base of the Carboniferous System is probably the most intractable problem in Scottish Carboniferous chronostratigraphy. This is because the strata that straddle the boundary are palaeontologically almost barren. Older schemes approximated the boundary with the base of the Cementstone Group (now termed the 'Ballagan Formation'), which was then seen as marking a major facies change from 'Old Red Sandstone' to 'Carboniferous' lithologies. These schemes have long been recognized as placing the boundary too high (e.g. Waterston in Craig, 1965) but persisted because of their convenience and because of the difficulties in recognizing another boundary position between the upper Tournaisian miospore assemblages of the Ballagan Formation and the Upper Famennian fish faunas of the Upper Old Red Sandstone (now placed in the Stratheden Group). Lumsden (1982) suggested that the term 'Devono–Carboniferous' should be used for the intermediate strata of unresolved age, but the lithostratigraphical revisions of Paterson and Hall (1986) also created a radically different structure in which the calcrete beds of the Kinnesswood Formation, by being placed within the Inverclyde Group, became increasingly linked to Carboniferous lithostratigraphies and treated as part of the Carboniferous System (Browne *et* at, 1999). Recent miospore finds (reported in Browne *et al.,* 1999) appear to confirm that much of the Kinnesswood Formation is of Carboniferous age and that the Devonian–Carboniferous boundary lies within this formation. Although the first calcrete is a closer approximation in time to the Devonian–Carboniferous boundary than the first cementstone, it should not be forgotten that this remains a lithological and possibly diachronous boundary.

Geological setting

The origins of the Midland Valley of Scotland lie in the crustal processes of early to middle Palaeozoic times, when it and the Southern Uplands were accreted as separate terranes to the Laurentian continental margin by sinistral strike-slip (Phillips *et al.,* 1998). By late Devonian times it had become, through reactivation of its boundary faults, a subsiding rift valley (Leeder, 1988) though deep structural complexities caused complex and changing patterns of subsidence within the graben. Furthermore, tectonic activity continued to influence the pattern of sedimentation during Lower Carboniferous times (Monro, 1982b; Stedman, 1988; Read, 1988, 1989; Rippon *et al.,* 1996).

In late Devonian times, braided river systems derived from the Dalradian Highlands to the north-west and flowing eastwards were depositing, in the subsiding Midland Valley, red cross-bedded sandstones that often have erosive conglomeratic bases and which fine-up into silty mudrocks deposited on floodplains. Increasingly, however, channel tops and floodplain surfaces were stabilized long enough for soil-forming processes to begin to operate, giving rise to calcrete horizons. These become increasingly common in the basal part of the Inverclyde Group Kinnesswood Formation, which straddles the Devonian–Carboniferous boundary.

The passage from the Stratheden Group (late Devonian) into the Kinnesswood Formation (Fammenian to early Tournaisian) is usually conformable, but in the west there may be a small erosional break between these units and in places the Kinnesswood Formation overlaps onto much older rocks. The soil calcretes indicate an arid or semi-arid environment with an average temperature of at least 16° C and a moderate but seasonal rainfall. This is consistent with the reconstructed palaeolatitude a few degrees south of the equator. Towards the top of the Kinnesswood Formation these calcretes become highly developed and may indicate depositional breaks in excess of a hundred thousand years.

The Kinnesswood Formation is overlain conformably by the Ballagan Formation. In places there is a transition with the characteristic facies of the two formations interbedded and it is possible that the boundary may be diachronous. The mudrock and cementstone facies, which typify the Ballagan Formation were deposited in a wide flat lagoonal or protected coastal-plain environment ((Figure 2.3)a). The dolomitic character of the cementstones, the presence of desiccation cracks and occurrences of gypsum and pseudomorphs after halite all indicate that conditions were still arid to semiarid and that salinities in the water bodies, though variable, were often hypersaline. The mudrocks appear to have been deposited during wetter intervals whereas the cementstones were formed when conditions were drier. The rhythmic alternations of the mudrocks and cementstones and the bundling of cycles into units, which may be separated by thin sandstones, suggest a system that was highly sensitive to small climatic changes and that may record climatic variations on various timescales of tens and hundreds of thousands of years. As is typical of such a high-stress environment, faunas are sporadic and sparsely developed but suggest an intermittent distal marine connection, with marine waters entering from both the east and the west.

The passage from the Ballagan Formation to the Clyde Sandstone Formation (upper Tournaisian), which is the uppermost formation in the Inverclyde Group, may again be regionally diachronous but in sections is usually sharp and sometimes erosive. It shows a reversion to a subaerial fluvial deposition environment similar to that of the Kinnesswood Formation, which may reflect uplift and rejuvenation of the sediment source areas. Like the Kinnesswood Formation, the basal parts of the Clyde Sandstone Formation may contain calcrete deposits. In addition, there may be carbonate conglomerates with concentrations of calcrete and cementstone fragments eroded from earlier deposits. Towards the top of the Clyde Sandstone Formation, however, the presence of coalified plant material, root beds and thin coal seams indicate that the climate was becoming more humid. This may reflect the northerly drift of the area towards the equator.

The Clyde Sandstone Formation is principally developed in the western part of the Midland Valley but is also recognized in East Fife (Browne *et al.,* 1999). The absence of an equivalent of the Clyde Sandstone Formation in the Lothians (Figure 2.2) may indicate that deposition of finer-grained sediments persisted here while more fluvial deposition took place elsewhere. It could, however, also be at least partly an effect of erosion linked to the Mid-Dinantian Break, which has recently been recognized as having occurred at about the Tournaisian–Viséan boundary and which terminated the deposition of the Inverclyde Group and brought about a major change in the palaeogeography of the Midland Valley (Paterson *et al.,* 1998). This break may have been caused by transpressional dextral shear and re-activation along pre-existing fault lines (Paterson *et al.*, 1998) which caused erosion of Inverclyde Group beds over structural highs. Subsequent depositional patterns were also influenced by continued faulting and differential subsidence over blocks and basins that became apparent at this time. In addition, there was a major reversal of the regional gradient of current flow from its previously eastward direction to westwards within the Midland Valley.

Following the Mid-Dinantian Break two new elements become important in the palaeogeography of the Midland Valley and influence depositional patterns throughout the Strathclyde Group and Clackmannan Group. Firstly, there was a major river system, which flowed southwards down the area that is now the northern North Sea. This drained and transported sediment from the Caledonian hinterland and from the Fenno-Scandinavian area (Whyte, 1994). Although the river system and its deltas at times bypassed the Midland Valley, the latter formed a sediment trap on its western flank (Figure

2.3)b. Secondly, there was the copious eruption of the lavas and tuffs of the Clyde Plateau Volcanic Formation and of the Arthur's Seat Volcanic Formation and Garlton Garlton Hills Volcanic Formation (Figure 2.2), which together with later volcanism affected both contemporaneous sedimentation patterns in the Strathclyde Group and later deposition throughout the Carboniferous Period.

The volcanic activity that produced the Clyde Plateau Volcanic Formation, persisted until Brigantian times and produced thicknesses of volcanic material that were in excess of 1 km. The lavas were principally distributed in a great arc from West Fife through the Touch Hills, Campsie Fells and Kilpatrick Hills into Renfrew and Ayrshire. At their southern extreme they reached Strathaven in Lanarkshire and a tongue of lavas also extended to the Rashiehill area of Stirlingshire (Anderson, 1963). Even at an early stage in the formation of the Strathclyde Group these volcanics formed a barrier across the Midland Valley and separated an Ayrshire Basin or Shelf, on which little or no deposition took place, from areas to the north-east. Water was often ponded up between the deltas and the lavas to form enclosed or semi-enclosed water bodies (Figure 2.3)b, which have collectively been termed 'Lake Cadell' (Greensmith, 1965, 1968). The water bodies, which were often stratified, at times covered areas of 2000–3000 km^2 (Loftus, 1984). Deposition from these produced the rhythmic sequences of mudrocks, oil shales and lacustrine limestones, which make up the Gullane Formation and West Lothian Oil-Shale Formation of the Lothians and West Fife (Figure 2.2). The situation was, however, very dynamic and within these formations there are also phases of delta progradation and marine incursion. The lacustrine conditions may occasionally have extended into East Fife but the successions here show greater deltaic and marine influences and interaction. Barriers may have existed between Fife and the Lothians and their position may have been partly influenced by the Garleton Hills Volcanic Formation, which although overstepped by the Gullane Formation, reached thicknesses in excess of 0.5 km (Lagios, 1984). Marine bands such as the Macgregor Marine Bands in the Pittenweem Formation resulted from incursions from the east and south-east (Wilson, 1974, 1989). The greatest advance of the delta complex within the deposition of the Strathclyde Group took place during Asbian times and led to the deposition of the sandstone-dominated Sandy Craig Formation of East Fife and the Aberlady Formation (Bilsdean Sandstone Member) in East Lothian (Figure 2.2). It is at this time that the Lake Cadell water masses were most clearly isolated, and thick oil shales (the West Lothian Oil-Shale Formation) and lacustrine limestones (including the Burdiehouse Limestone) developed. The occurrence of calcretes in both the Sandy Craig Formation and the Bilsdean Sandstone Member indicates a short phase of semi-arid climate. This contrasts with the humid equatorial conditions that otherwise seem to have prevailed throughout the deposition of the Strathclyde Group.

Towards the top of the Strathclyde Group the Clyde Plateau Volcanic Formation became increasingly overstepped and the palaeogeography of Lake Cadell began to break down. The volcanics themselves had been deeply weathered in the tropical climate and as deposition recommenced the decomposition products were locally re-distributed to form the diachronous mantle of the Kirkwood Formation (Figure 2.2). Elsewhere, in strata of the Lawmuir Formation and Pathhead Formation and their equivalents (lower Brigantian), deltas interacted with marine incursions to form Yoredale-type cycles. Although marine conditions from the south-east extended far into the Midland Valley on several occasions, both the marine shales and limestones and the intervening clastics show considerable lateral facies variation and there are problems in the correlation of horizons. The situation is complicated by disconformities within the sequence (Whyte, 1981), which appear to be the result of localized tectonic activity. In some cases marine limestones were exposed to pedogenic modification and bleaching. A non-marine limestone, the Baldernock Limestone, is also present towards the top of the Lawmuir Formation (Macgregor *et al.,* 1925; Whyte, 1994). Further stratigraphical complexities are created by the volcanic activity of the Bathgate Hills Volcanic Formation, which had commenced earlier and which is concentrated in West Lothian and West Fife.

The Lower Limestone Formation (upper Brigantian) shows a continuation of this Yoredale cyclicity, with well-developed and extensive marine horizons. The basal Hurlet Limestone is usually regarded as the first marine horizon to have extended throughout the Midland Valley (Browne *et al.,* 1999) (Figure 2.2) and (Figure 2.4), though there may still have been persistent island areas on topographical highs in the extinct volcanic areas of the Campsie Fells and Renfrewshire Hills as well as the active volcanoes of the Bathgate Hills. The Blackhall Limestone, in the centre of the Lower Limestone Formation, shows some interesting facies variations. In the west its lower part is lagoonal in character and may have been isolated by barriers relating to the Bathgate Hills Volcanic Formation and the Burntisland High ((Figure 2.3)c). In the upper parts of the limestone, unusual, and often crinoid-rich, mud-mound developments in West Fife may also have been controlled by these structural factors. The marine shales above the limestone contain the Neilson Shell Bed Fauna, which has proved to be a valuable index fauna for correlating this horizon. Isopach maps and lithological variations (Goodlet, 1957; Browne and Monro, 1989) show that structural features had a great effect on depositional patterns, and exposure surfaces in the sequence indicate continued minor tectonic activity. The thin limestones, the Hosie Limestones, at the top of the formation (Figure 2.4) form two composite marine bands separated by an extensive coal and fireclay horizon, which may also indicate a depositional break.

The upward passage from the Lower Limestone Formation (upper Brigantian) into the Limestone Coal Formation (Pendleian) is accompanied by a marked shift in facies, which may reflect a regional uplift (Goodlet, 1959). As its name indicates, the Limestone Coal Formation is dominated by delta-top facies of mudrocks and sandstones, in which coal seams are extensively developed ((Figure 2.3)d). Marine limestones, however, do not occur and, although there are several horizons with *Lingula* and/or non-marine bivalves, there are only two fully marine mudrock horizons within the formation. The upper of these, the Black Metals Marine Band, lies about the centre of the formation and the lower, the Johnstone Shell Bed, lies about halfway between the Black Metals Marine Band and the base of the formation (Figure 2.5). The sandstones, which may be sheet or channel sands, reach their greatest cumulative thickness in areas of 1966). Structural controls continued to influence sedimentation patterns during the deposition of the formation (Browne and Monro, 1989), though it was during this interval that the lava topography of the Renfrew Hills was finally over-topped by sediment (Richey *et al.,* 1930). Active volcanism was taking place locally in West Lothian, Fife and North Ayrshire (Francis in Craig, 1991) ((Figure 2.3)d).

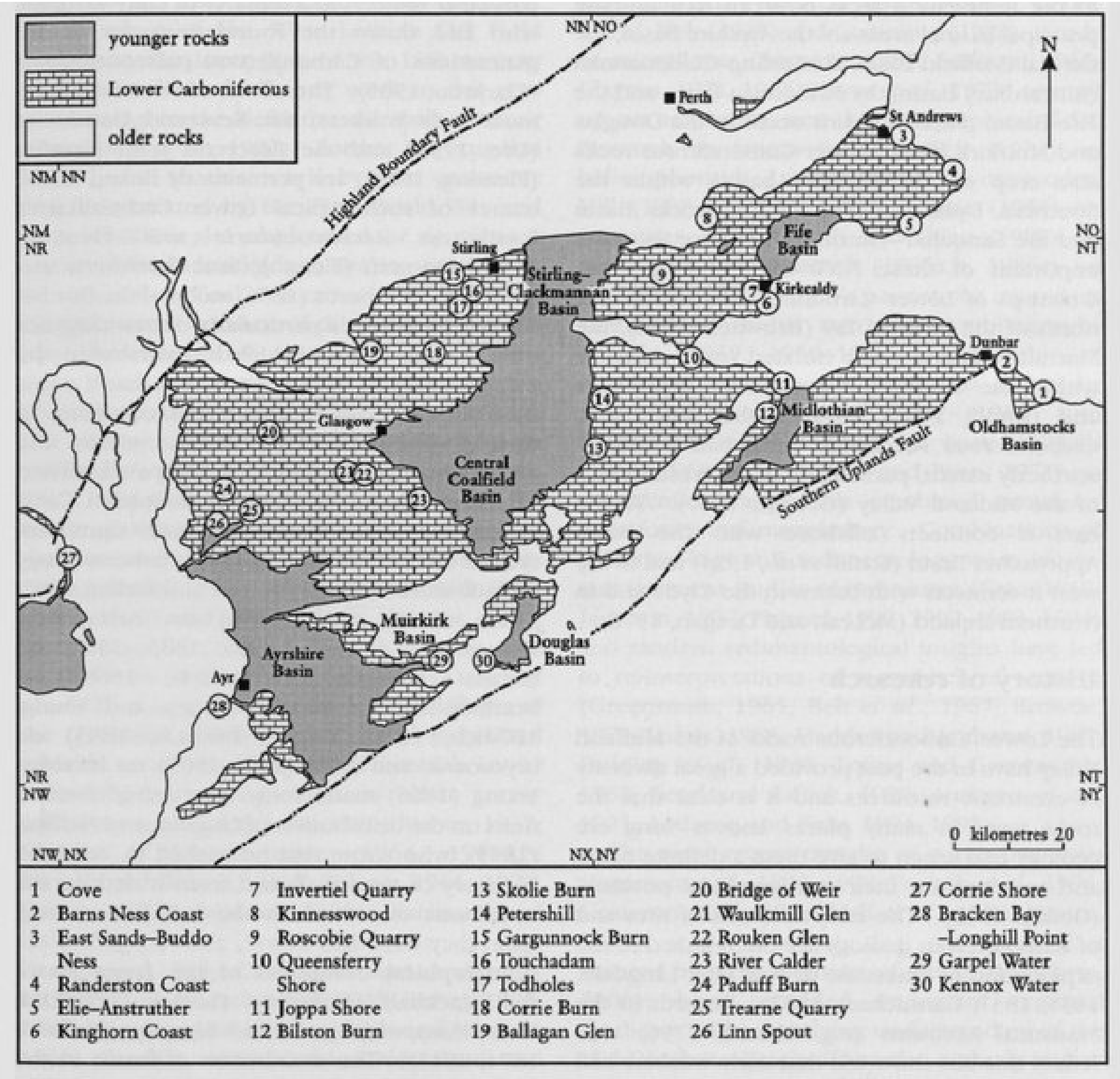
Conditions in the Upper Limestone Formation (late Pendleian to Arnsbergian) show a return to a Yoredale style of cyclicity, with alternations of deltaic and marine conditions similar to that of the Lower Limestone Formation and with a similar palaeogeography (Browne and Monro, 1989). The marine limestones tend to be thinner and more argillaceous than those of the Lower Limestone Formation and their faunas are less diverse (Wilson, 1967). However, the principal marine bands, which in ascending order are the Index Limestone, Lyoncross Limestone, Orchard Limestone, Calmy Limestone, Plean (1, 2 and 3) Limestones, and Castlecary Limestone (Figure 2.5), can be correlated over wide areas. In places they can be traced laterally into bands that contain *Lingula.* There are several other bands containing *Lingula* and shales with non-marine bivalves in the sequence. A greater proportion of limestone in the west of the Midland Valley may indicate more marine conditions in this area (Francis in Craig, 1991). In places, and particularly towards the top of the succession, there are minor local disconformities and erosively based sandstones that cut out some limestones including the Castlecary Limestone. Some minor volcanism also occurred in Fife and north Ayrshire (Francis in Craig, 1991).

GCR site coverage

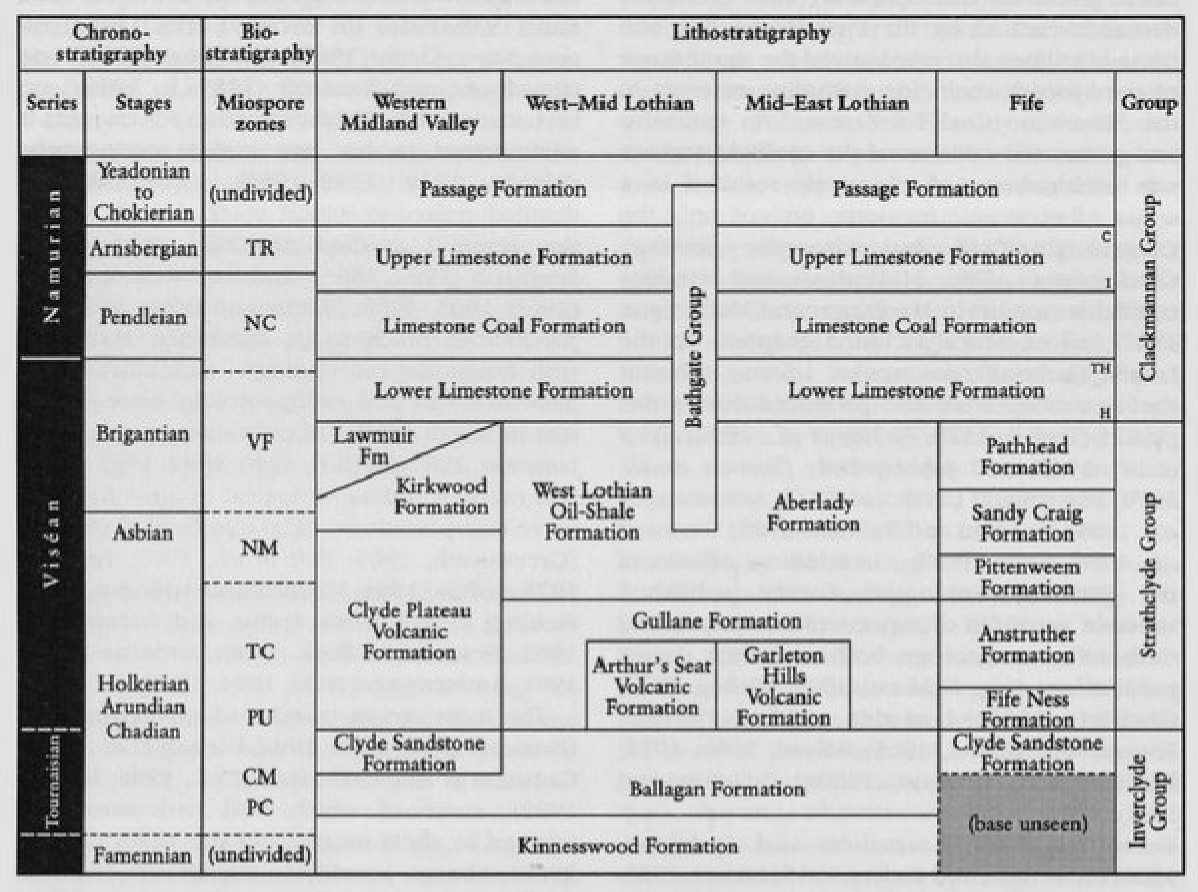
The suite of sites chosen to represent the Lower Carboniferous rocks of the Midland Valley (Figure 2.1) is designed to exemplify both the sequence and its variation in as far as this can be done from surface exposures. Although most sites lie within the major basinal areas, the Garpel Water and Kennox Water GCR sites represent successions within smaller basins in the south-west of the Midland Valley, and the Corrie Shore GCR site lies on the western margin of the largely offshore East Arran (Clyde) Basin. The successions at Cove and Barns Ness Coast make up an almost complete Dinantian succession and lie outside the eastern end of the Midland Valley in the Oldhamstocks Basin. These exposures form an important link between successions in the north of England and those in the Midland Valley. In East Fife the coastal successions of Elie–Anstruther and Randerston Coast illustrate successions close to the thickest known developments of the Strathclyde Group and Lower Limestone Formation. In contrast, a thinner development of an important part of the Strathclyde Group is seen to the north at East Sands–Buddo Ness, and contrasting laterally equivalent facies, including oil shales, are exposed at Queensferry Shore. Although only the top of the Inverclyde Group is seen in East Fife, it is well represented in the Gargunnock Burn, at the classic locality of Ballagan Glen and at Bracken Bay–Longhill Point, which also has important faunal and floral records. The basal formation of the Inverclyde Group (the Kinnesswood Formation) occurs over a structural high at Kinnesswood (the type locality) where it is uniquely disconformably overlain by a thin sequence belonging to the Pathhead Formation. Structural controls on sedimentation are also demonstrated in the distribution of the palaeontologically significant sites at Invertiel Quarry, Roscobie Quarry and Petershill. Lateral facies variations in the variable sequences of the Lawmuir Formation are beautifully displayed at Touchadam and Todholes, and the complexities of upper Brigantian stratigraphy are further exemplified at the Paduff

Burn, Bridge of Weir, River Calder, Kinghorn Coast, Skolie Burn, Bilston Burn and Corrie Burn GCR sites. The latter, like Trearne Quarry, also has important palaeontological interests. Although represented at a number of sites, such as Paduff Burn, Kennox Water and the unusual sequence at Corrie Shore, the Limestone Coal Formation is poorly exposed and principally known from subsurface and borehole data; accordingly, it is not well represented in the site coverage. The more uniform sequence of the Upper Limestone Formation is typified by the complementary successions at Rouken Glen and Waulkmill Glen in the west and at Joppa Shore and Bilston Burn in the east Linn Spout is a further lithologically and palaeontologically valuable site for this formation.

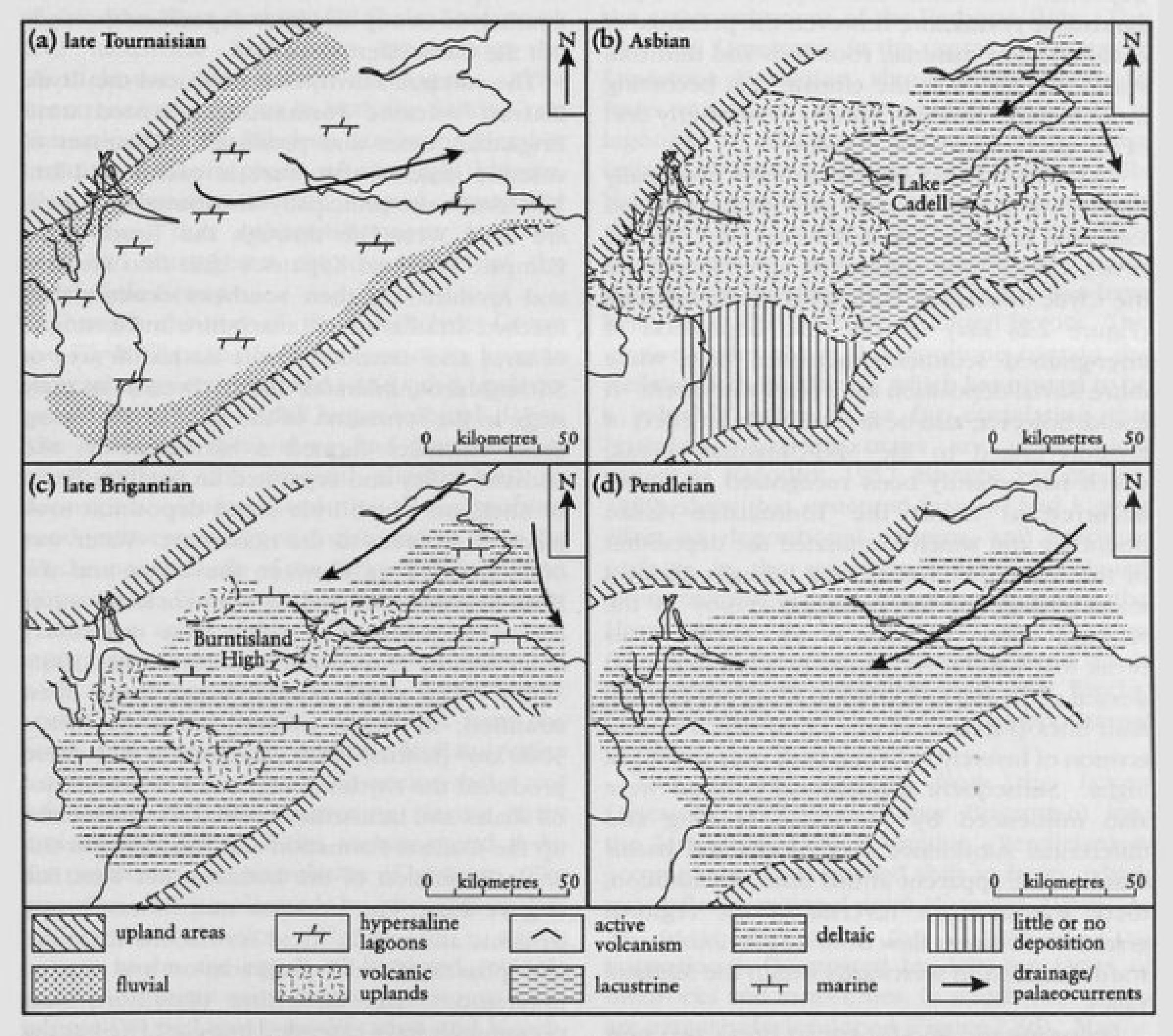
[References](#)



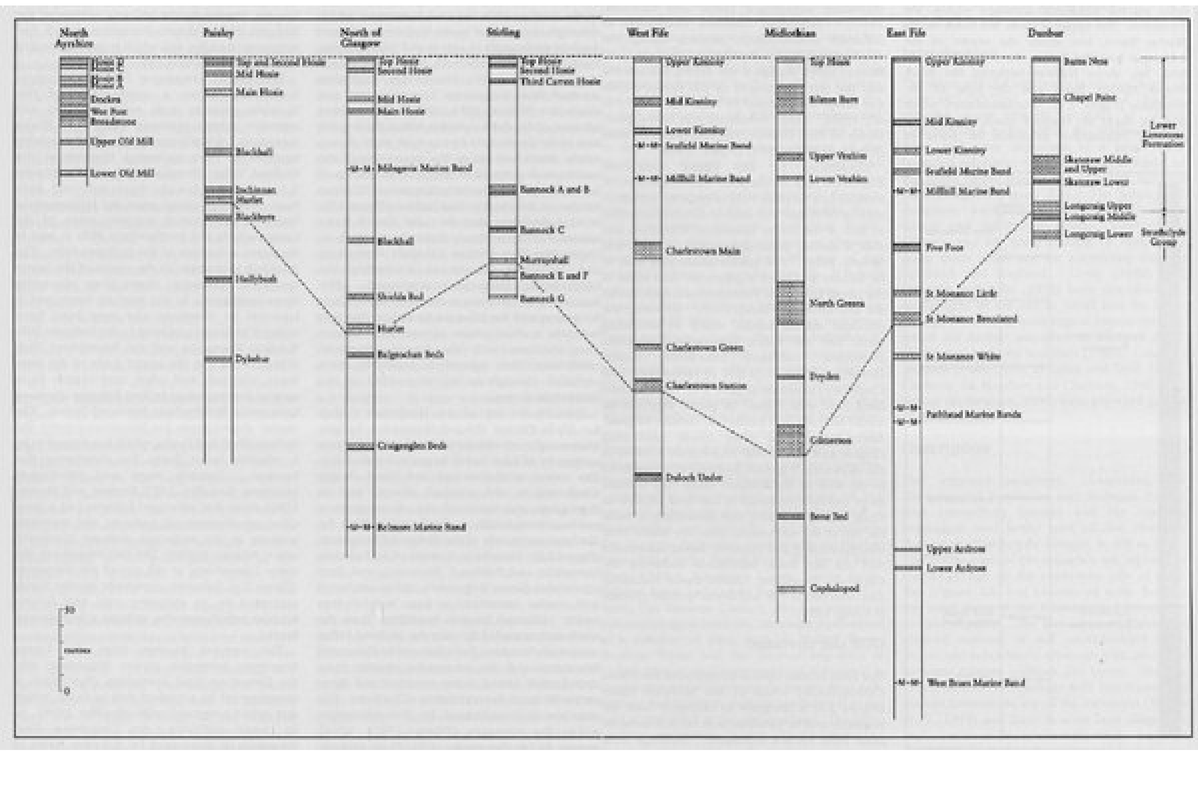
(Figure 2.1) Geological map of the Midland Valley Basin showing the distribution of Lower Carboniferous outcrops, sedimentary basins and the location of GCR sites described in the text. Based on information from [British] Geological Survey maps of the area (principally Institute of Geological Sciences, 1979a).



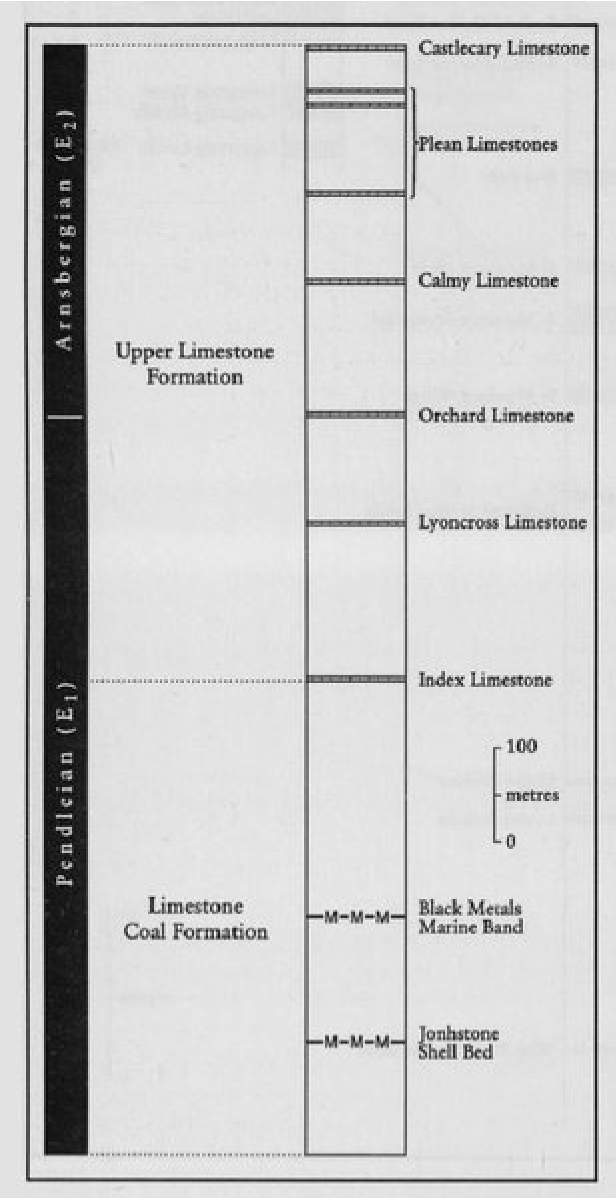
(Figure 2.2) Simplified Lower Carboniferous stratigraphical chart for the Midland Valley of Scotland. Note that below the Brigantian Stage, the position of stage boundaries is uncertain and that below the NM miospore zone only recorded zones are indicated. (H — Hurlet Limestone; TH — Top Hosie Limestone; I — Index Limestone; C — Castlecary Limestone.) The Bathgate Group comprises the Salsburgh Volcanic Formation, the Bathgate Hills Volcanic Formation and the Kinghorn Volcanic Formation. Based on various sources and including information from Whyte (1981), Chisholm et al. (1989) and Browne et al. (1996, 1999).



(Figure 2.3) Lower Carboniferous palaeogeographical reconstructions of the Midland Valley area: (a) late Tournaisian (Ballagan Formation, Inverclyde Group); (b) Asbian (Sandy Craig Formation, Strathclyde Group); (c) late Brigantian (Lower Limestone Formation, Clackmannan Group); (d) Pendleian (Limestone Coal Formation, Clackmannan Group). Based on various sources and including information from Craig (1991) and Whyte (1994).



(Figure 2.4) Correlation of the principal marine horizons in the Brigantian Lower Limestone Formation and uppermost part of the Strathclyde Group in the Midland Valley from North Ayrshire to Dunbar. Note that most of the named units figured here are, unless otherwise stated, limestones (names abbreviated). Based on various sources and including information from George et al. (1976), Cameron and Stephenson (1985), Wilson (1989) and Francis (1991).



(Figure 2.5) Simplified stratigraphy of the Limestone Coal Formation and Upper Limestone Formation of the Midland Valley (as typified by the Kincardine Basin succession) showing the position of the principal marine horizons. Based on Ramsbottom et al. (1978) and Cameron and Stephenson (1985). maximum subsidence (Read and Merriam,