British Lower Carboniferous Stratigraphy

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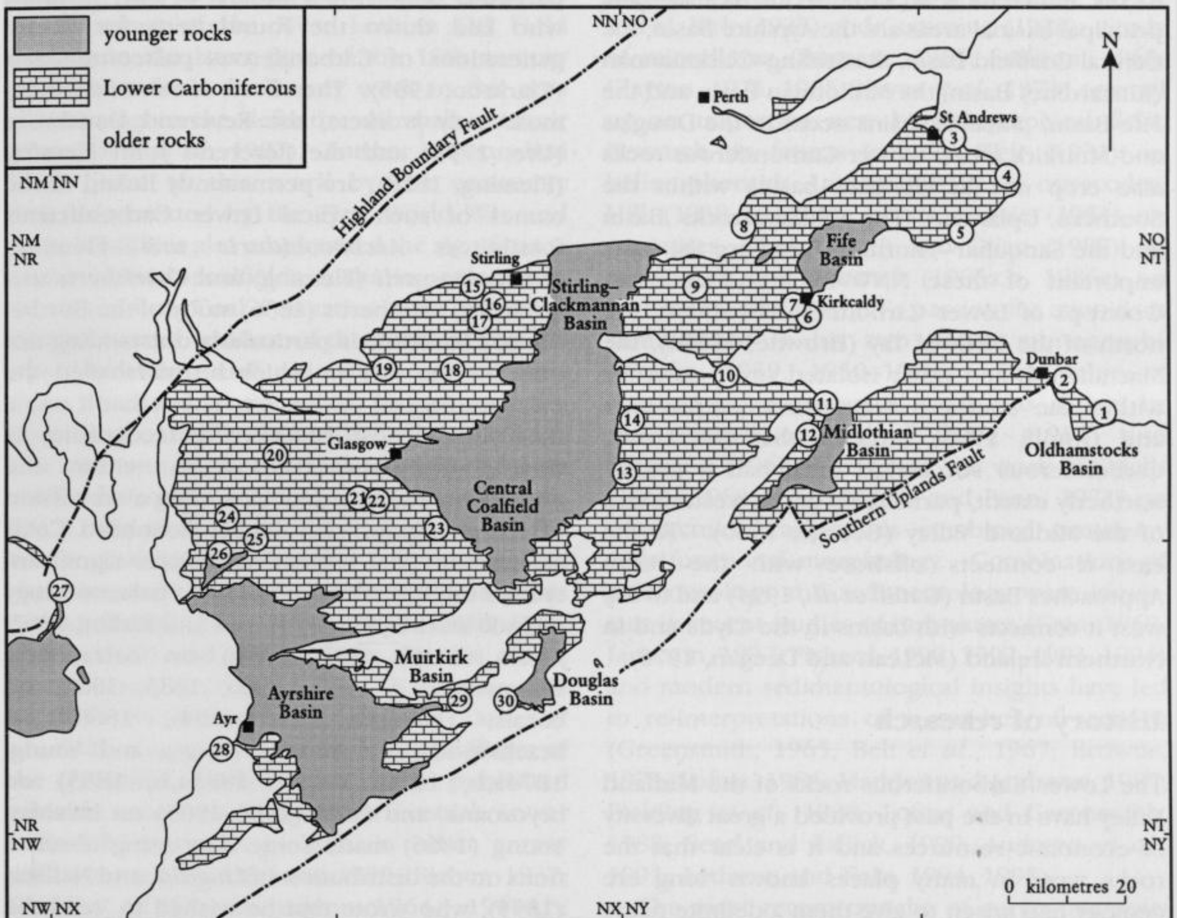
Chapter 2

Midland Valley Basin

M.A. Whyte

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



1 Cove	7 Invertiel Quarry	13 Skolie Burn	20 Bridge of Weir	27 Corrie Shore
2 Barns Ness Coast	8 Kinnesswood	14 Petershill	21 Waulkmill Glen	28 Bracken Bay –Longhill Point
3 East Sands–Buddo Ness	9 Roscobie Quarry	15 Gargunnock Burn	22 Rouken Glen	29 Garpel Water
4 Randerston Coast	10 Queensferry Shore	16 Touchadam	23 River Calder	30 Kennox Water
5 Elie–Anstruther	11 Joppa Shore	17 Todholes	24 Paduff Burn	
6 Kinghorn Coast	12 Bilston Burn	18 Corrie Burn	25 Trearne Quarry	
		19 Ballagan Glen	26 Linn Spout	

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).

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 Geikie (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

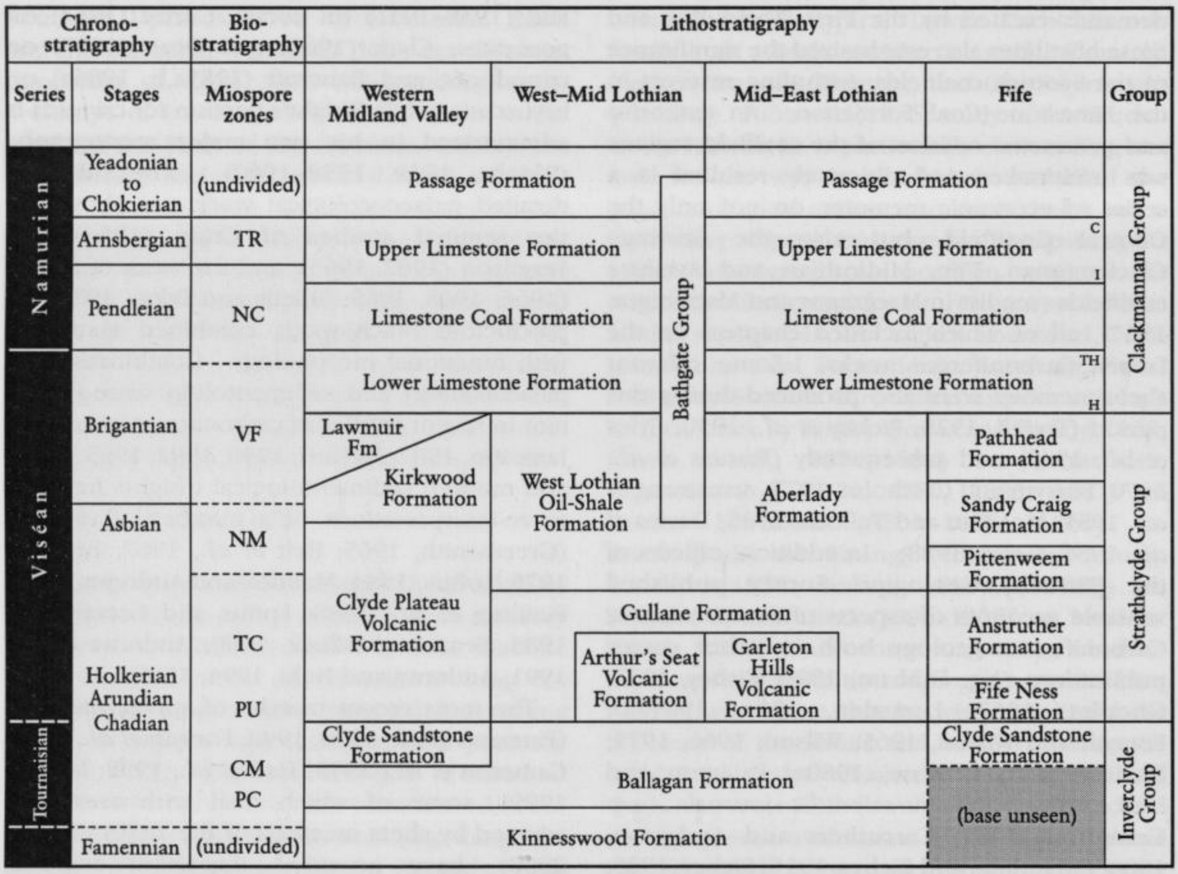


Figure 2.2 Simplified Lower Carboniferous stratigraphical chart for the Midland Valley of Scotland. Note that below the Brigantian Stage, the position of stage boundaries is uncertain and that below the NM miospore zone only recorded zones are indicated. (H – Hurlet Limestone; TH – Top Hosie Limestone; 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).

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 al.*, 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–E_1 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 al.*, 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 re-activation 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 2.3a). 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 semi-arid 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.

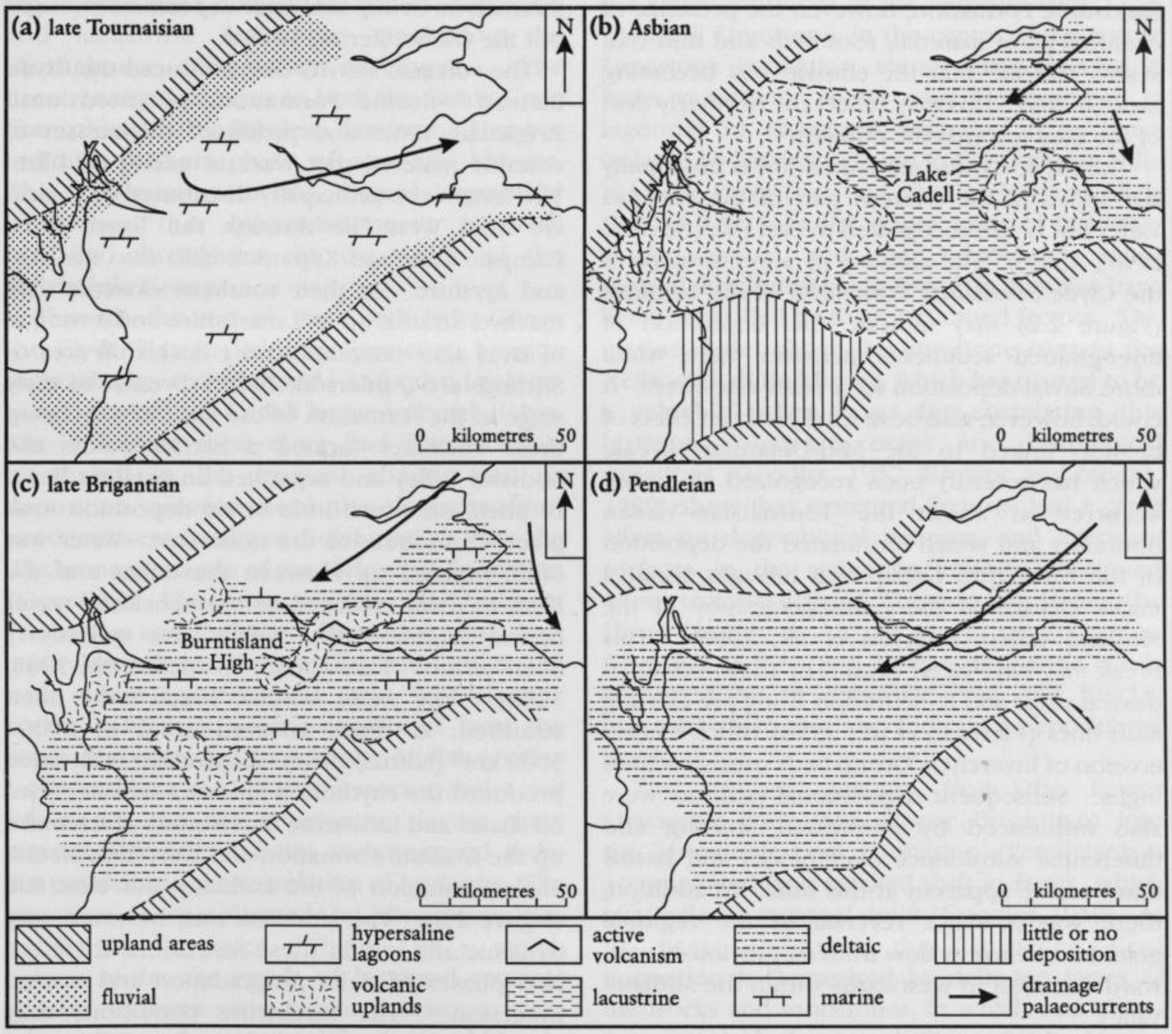


Figure 2.3 Lower Carboniferous palaeogeographical reconstructions of the Midland Valley area: (a) late Tournaisian (Ballagan Formation, Inverclyde Group); (b) Asbian (Sandy Craig Formation, Strathclyde Group); (c) late Brigantian (Lower Limestone Formation, Clackmannan Group); (d) Pendleian (Limestone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

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 2.3b). 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 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 2.3b), 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 Garlton 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) (Figures 2.2 and 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 2.3c). 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 2.3d). Marine limestones, however, do not occur and, although there are several horizons with *Lingula* and/or non-marine bivalves, there are only two

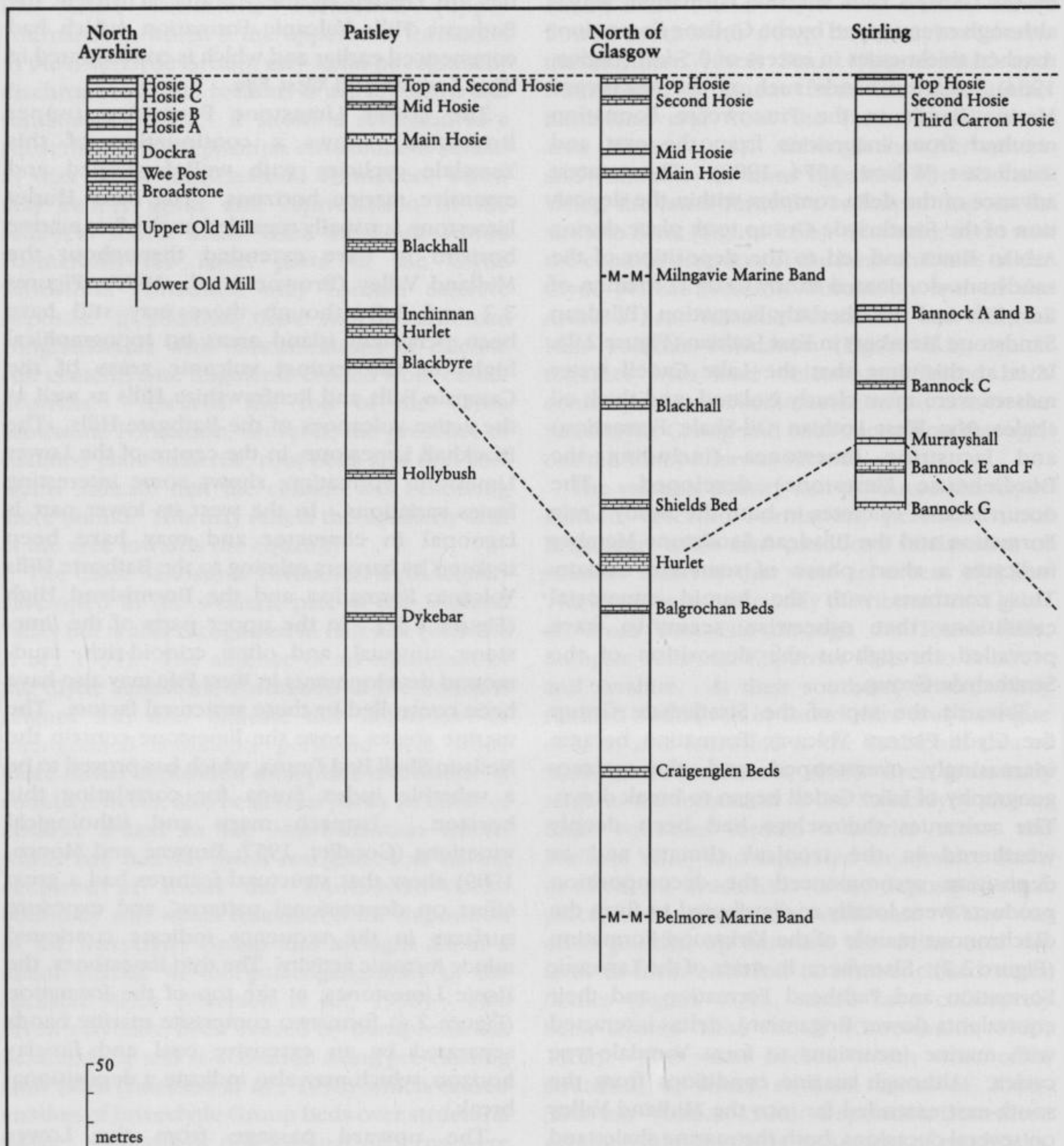
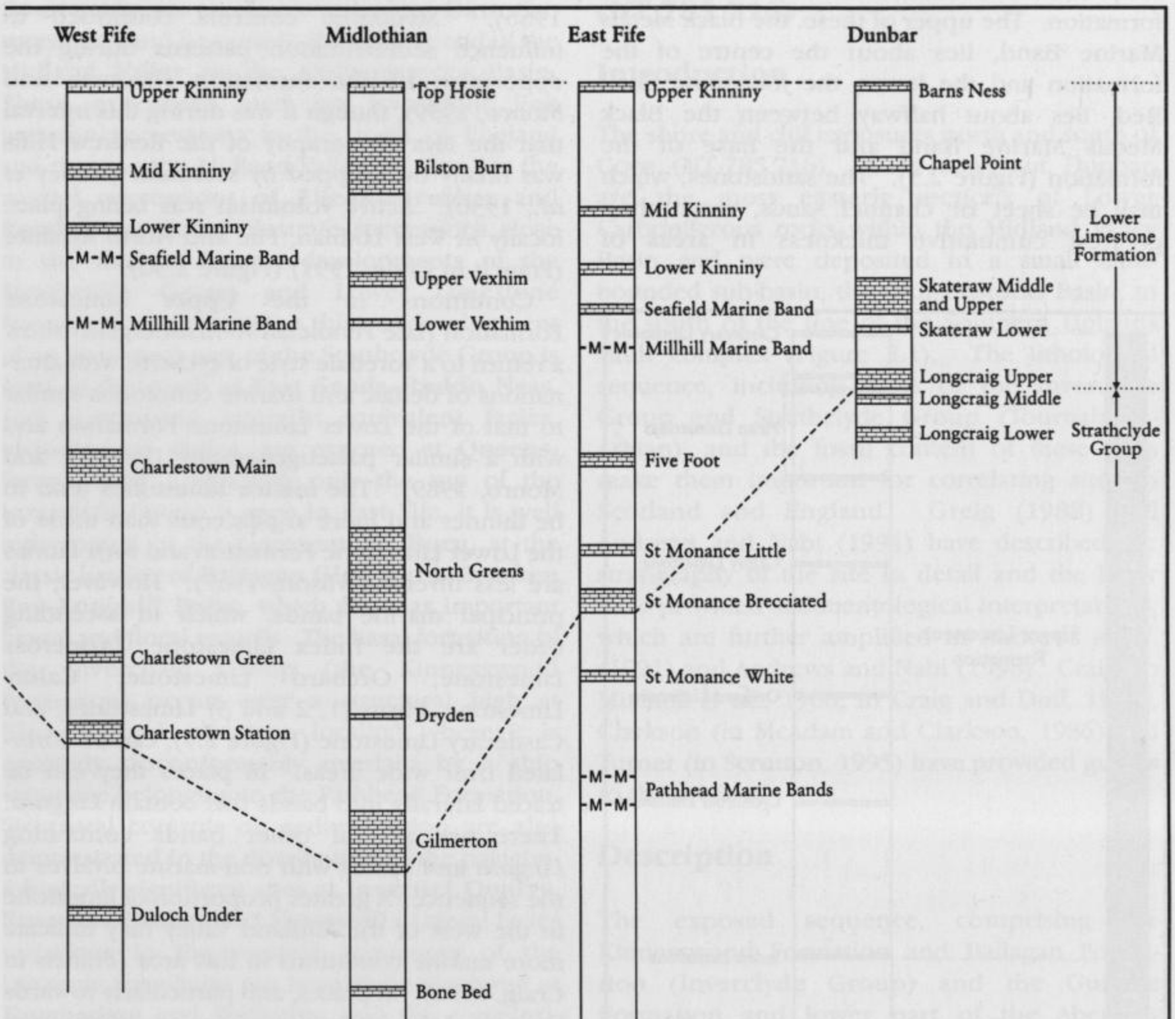


Figure 2.4 Correlation of the principal marine horizons in the Brigantian Lower Limestone Formation and uppermost part of the Strathclyde Group in the Midland Valley from North Ayrshire to Dunbar. Note that most of the named units figured here are, unless otherwise stated, limestones (names abbreviated).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


West Fife
Midlothian
East Fife
Dunbar
Upper Kinniny
Mid Kinniny
Lower Kinniny
M-M Seafield Marine Band
M-M Millhill Marine Band
Charlestown Main
Charlestown Green
Charlestown Station
Duloch Under
Top Hosie
Bilston Burn
Upper Vexhim
Lower Vexhim
North Greens
Dryden
Gilmerton
Bone Bed
Cephalopod
Upper Kinniny
Mid Kinniny
Lower Kinniny
Seafield Marine Band
M-M Millhill Marine Band
Five Foot
St Monance Little
St Monance Brecciated
St Monance White
M-M Pathhead Marine Bands
Upper Ardross
Lower Ardross
M-M West Braes Marine Band
Barns Ness
Chapel Point
Skateraw Middle and Upper
Skateraw Lower
Longcraig Upper
Longcraig Middle
Longcraig Lower
Lower Limestone Formation
Strathclyde Group

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 maximum subsidence (Read and Merriam, 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 2.3d).

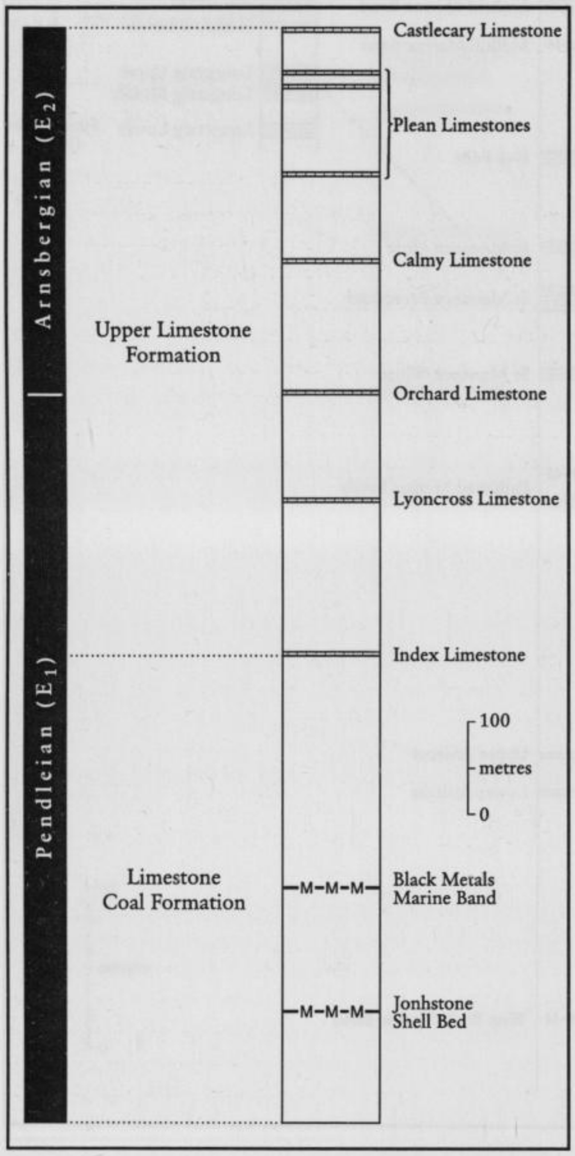


Figure 2.5 Simplified stratigraphy of the Limestone Coal Formation and Upper Limestone Formation of the Midland Valley (as typified by the Kincardine Basin succession) showing the position of the principal marine horizons. Based on Ramsbottom *et al.* (1978) and Cameron and Stephenson (1985).

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.

COVE, SCOTTISH BORDERS (NT 785 716)

Introduction

The shore and cliff exposures north and south of Cove (NT 785 716), 10 km south of Dunbar, are the most easterly sections of Lower Carboniferous rocks within the Midland Valley Basin and were deposited in a small fault-bounded sub-basin, the Oldhamstocks Basin, to the south of the line of the Southern Uplands Fault complex (Figure 2.1). The lithological sequence, including parts of the Inverclyde Group and Strathclyde Group (Tournaisian–Asbian), and the fossil content of these beds make them important for correlating sites in Scotland and England. Greig (1988) and Andrews and Nabi (1994) have described the stratigraphy of the site in detail and the latter have provided sedimentological interpretations, which are further amplified in Andrews *et al.* (1991) and Andrews and Nabi (1998). Craig (in Mitchell *et al.*, 1960; in Craig and Duff, 1975), Clarkson (in McAdam and Clarkson, 1986) and Turner (in Scrutton, 1995) have provided guides to the section.

Description

The exposed sequence, comprising the Kinnesswood Formation and Ballagan Formation (Inverclyde Group) and the Gullane Formation and lower part of the Aberlady Formation (Strathclyde Group), is 400 m thick. The lowest parts of the sequence are exposed at Hawk's Heugh on the north-west side of Pease Bay (Figure 2.6) but because of strike faulting the basal parts of the Kinnesswood Formation are not exposed. The Kinnesswood Formation (100 m) consists of red, cross-bedded sandstones and subordinate siltstones with abundant irregular calcrete nodules and layers. The calcretes become increasingly well developed and mature towards the top of the formation (Wright *et al.*, 1993) and there is some later diagenetic replacement of the calcite with silica. Scales of the fish *Holoptychius* have been recorded from this formation but appear to be absent in the uppermost 10 m (Clough *et al.*, 1910).

The basal boundary of the Ballagan Formation has recently been re-defined as the base of silty mudstones, which rest on the highest calcrete,

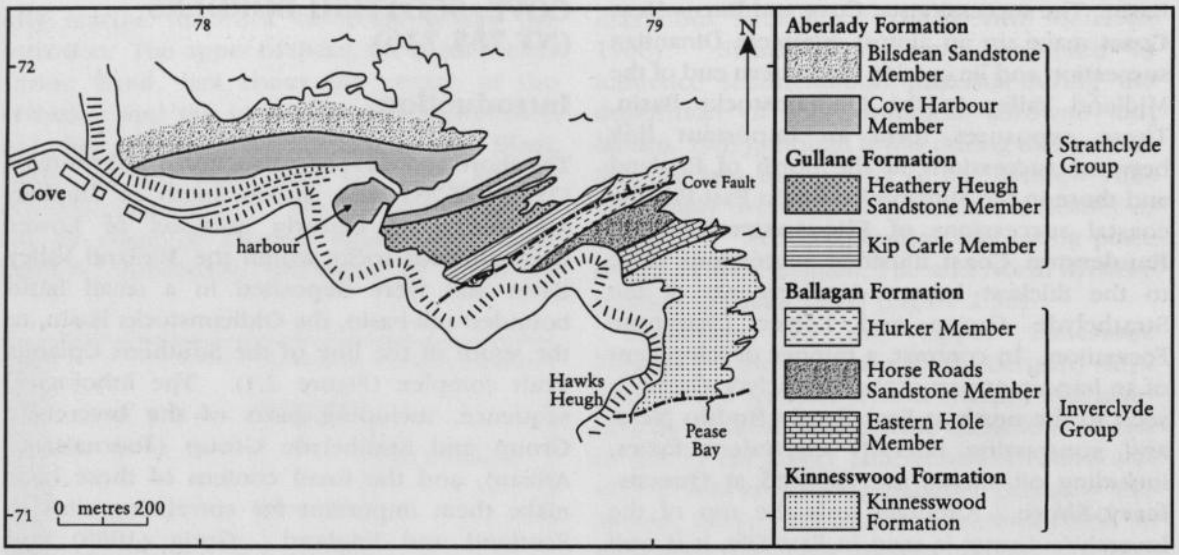


Figure 2.6 Geological map illustrating the distribution of Lower Carboniferous rocks at the Cove GCR site. Based on Craig and Duff (1975) and Andrews and Nabi (1994).

of the Kinnesswood Formation (Andrews and Nabi, 1994). The formation is characterized by nodular dolomitic cementstones interbedded with mudrocks, siltstones and fine sandstones of the Eastern Hole Member (31 m) and the Hurker Member (32 m) separated by the sandstones of the Horse Roads Sandstone Member (23 m). The basal laterally variable parts of the Eastern Hole Member are dominated by mudrocks within which Andrews *et al.* (1991) recognized an inclined erosion surface. The upper sandier parts of the member include a distinctive cementstone breccia, the Eastern Hole Conglomerate, whose sandy matrix also contains abundant plant (Scott and Rex, 1987) and fish remains. One metre higher, a sandy cementstone contains the marine bivalve *Sanguinolites*, fish scales and ostracodes. A marine fauna has also been detected in thin-sections from this bed (Andrews and Nabi, 1994). Palynological preparations from the lower part of the member contain miospores indicative of a Tournaisian age (CM Zone; see Figure 2.2) (Clayton, 1985). The Horse Roads Sandstone Member rests erosively on the Eastern Hole Member, and its fine- to medium-grained sandstones show a variety of sedimentary features including cross-bedding, ripple lamination and mudclasts. Wood fragments occur within several of the sandstone beds and one sandstone bed contains *Planolites* burrows. A distinctive feature of this member is the occurrence of large, highly spheroidal carbonate concretions (cannonballs) up to 2 m across. The Hurker Member, marked by the reappearance of the cementstone facies, is less well exposed than the rest of the Ballagan Formation and is disturbed and truncated by a branch of the east–west strike fault known as the 'Cove Fault'. The uppermost bed of the member has been interpreted as a nodular calcrete (Andrews and Nabi, 1998).

The Gullane Formation is represented in the Cove section by two members, the Kip Carle Member (49 m) and the Heathery Heugh Sandstone Member (65 m). The Kip Carle Member, which is also the lowest unit in the Strathclyde Group, is distinguished by the appearance of thick sandstones with associated coals and carbonacous mudrocks, which become more prominent in the upper part of the member. As this lithofacies develops, the cementstones of the underlying Ballagan Formation disappear. The sandstones may have basal erosion surfaces and contain cross-bedding, soft-sediment deformation, ripple marks and shrinkage cracks. Rootlet beds containing *Stigmaria* also occur and there is an abundance of other carbonized plant material. Ironstone nodules occur in some of the mudstones, and pyrite is commonly present. Bivalves and ostracodes have also been recorded from this part of the section. The Heathery Heugh Sandstone Member is predominantly composed of thick- to medium-bedded sandstones. These are generally of medium grain-size, but coarser bands occur and there are interbedded mudstones in places. The sandstones are marked by planar and trough cross-bedding and in places there is extensive convolution of the bedding. Desiccation structures and bioturbation are also present. Root beds occur rarely, but one horizon is well known for its plant remains (Scott *et al.*, 1984).

The succeeding Cove Harbour Member (77 m) of the Aberlady Formation (Figure 2.7) contains a mixed assemblage of thin- to medium-bedded sandstones, siltstones and mudrocks with associated ironstones and root beds. The most important elements within this member are the Cove Lower Marine Band at the base, the Cove Upper Marine Band about 20 m above the base, and the Cove Oil Shale about 60 m above the base. The two marine bands are exposed

Figure 2.7 Outcrops of the lower part of the Cove Harbour Member (Aberlady Formation) east of Cove Harbour. The topmost beds of the underlying Heathery Heugh Sandstone Member (Gullane Formation) can be seen in the near cliffs to the right. The large block (lower centre) is approximately 0.8 m long. (Photo: M.A. Whyte.)

within Cove Harbour. Faunal lists (Wilson, 1954; Wilson, 1974) have been summarized by Greig (1988) and show that these horizons are of Asbian age. The Cove Oil Shale is exposed on the foreshore to the north of the harbour and is a thin brownish shale with pyrite, plant material, including *Sphenopteris* fronds, and fish remains. In the uppermost parts of the member above the oil shale there are some carbonate units interpreted as calcretes (Andrews and Nabi, 1998). The overlying Bilsdean Sandstone Member marks a return to predominantly sandstone deposition, but only the basal few metres of this lie within the site.

Interpretation

The section at Cove is the only well-exposed sequence of lowermost Carboniferous rocks within the Cockburnspath Outlier. These rocks were deposited in a small depositional basin (Oldhamstocks Basin) to the south of the Southern Uplands Fault and on the flanks of the Southern Uplands Massif. The section shows extremely clearly the transition from the palaeosols and fluvial strata of the Kinnesswood Formation to the lake precipitates and floodplain deposits of the Ballagan Formation. The lithological changes from the Ballagan Formation to the wetter and swampier floodplain environments of the Kip Carle Member and the marine-influenced coastal floodplains of the Cove Harbour Member are also uniquely well displayed. The sequence is punctuated by several developments of fluvial channel sandstones, often with erosive bases, and the erosion surface within the Eastern Hole Member has been interpreted as a terrace cut into floodplain strata (Andrews *et al.*, 1991). The sequence thus contains crucial evidence of palaeoenvironmental and climatic change in the Lower Carboniferous sequence and of the derivation of sedimentary materials.

The section at Cove is critical in the correlation of Scottish and English successions. The correlation of the Cove Marine Bands with the MacGregor Marine Bands of the Lothians and Fife (Wilson, 1974, 1989) and with the Lamberton Limestone and Dun Limestone of Northumberland (Wilson, 1954) are a particularly important link between the two areas based on faunal evidence (Wilson, 1954; Greig, 1988). The composition of the faunas indicates an Asbian age (Wilson, 1989). Asbian goniatites have been found at this horizon in a nearby stream exposure (Currie, 1954). In addition, the carbonaceous beds of the Kip Carle Member can be equated with the Scremerston Coal Group of Northumberland (Greig, 1988), and the calcretes in the Cove Harbour Member have been compared to units in the Sandy Craig Formation of East Fife (Andrews and Nabi, 1994, 1998) and provide evidence of a semi-arid phase within what is a generally humid interval. Palynological work and the dating of the basal beds of the Ballagan Formation (Clayton, 1971; Neves *et al.*, 1973) contribute to this biostratigraphical evidence, and the position of the base of the Carboniferous System is further constrained by the records of the Devonian fish *Holoptychius* (Clough *et al.*, 1910).

Conclusions

The Cove GCR site is important as it allows a well-exposed, major Carboniferous section to be examined with representatives of the Inverclyde Group (Kinnesswood Formation and Ballagan Formation) and Strathclyde Group (Gullane Formation). The junction between the Kinnesswood Formation and Ballagan Formation, which is apparently conformable, has been dated palynologically as late Tournaisian in age and the base of the Carboniferous System probably lies within the Kinnesswood Formation. Higher beds consist of clastic deposits (sandstones and mudrocks), including representatives of the Scremerston Coal Group and, above, the Cove Marine Bands and associated strata. The sedimentology of these beds provides a unique insight into the interaction between fluvio-deltaic environments and palaeoclimatic changes within the Oldhamstocks Basin. The marine faunas and the biostratigraphically useful fossil spores make this a vital section in correlating sites in Scotland and England.

BARNS NESS COAST, EAST LOTHIAN (NT 697 782–NT 745 753)

Introduction

The coastal exposures between Lawrie's Den and Skateraw, 2–7 km south of Dunbar (NT 697 782–NT 745 753), are the best natural exposures of the Lower Limestone Formation and of the topmost beds of the Strathclyde Group (Aberlady Formation) in the south-east of the Midland Valley. The succession consists of cyclical sequences of fossiliferous marine limestones and mudrocks passing up into deltaic mudstone–sandstone units, which are often capped by thin coals. The different marine bands have distinctive features and the section is a vital link in correlating between sites in Scotland and England. Davies *et al.* (1986) summarized the geology and previous work on the area. Guides to the shore exposures between Barns Ness and Catcraig have been provided by Craig (in Mitchell *et al.* 1960; in Craig and Duff, 1975) and Clarkson (in McAdam and Clarkson, 1986).

Description

The geological succession at this site (Figure 2.8) is displayed, almost in full, on the foreshore between Catcraig and Barns Ness (NT 714 773–NT 723 773). Foreshore outcrops along strike between Barns Ness and Chapel Point (NT 723 773–NT 740 758) display the upper parts of this succession and provide a link to the outcrops of the upper half of the sequence at Skateraw. North of Catcraig and White Sands, complex outcrops in the vicinity of Millstone Neuk and Lawrie's Den provide lateral equivalents to the upper parts of the sequence.

The lowest beds of the succession are the Longcraig Middle Limestone (2 m) and an underlying marine bioturbated sandstone (*c.* 2 m), which, with an overlying fireclay, coal and marine mudstone, belong to the Longcraig Member of the Aberlady Formation (Strathclyde Group). The Longcraig Middle Limestone is a nodular argillaceous limestone, which contains towards its top a well-developed coral biostrome dominated by compound corals (Macaroni Rock). The corals are well displayed on the foreshore in front of the limekilns at Catcraig, in exposures, which also strikingly show the basin-like hollows that mark the upper surface of the limestone. These potholes, which are infilled with clay, are a karstic solution feature linked to palaeosol formation, and stigmarian roots and rootlets extend down from the coal into the limestone. The rootlets are often surrounded by sideritic rhizocretions and within the limestone there has been a development of pedogenic carbonate concretions. This Carboniferous soil

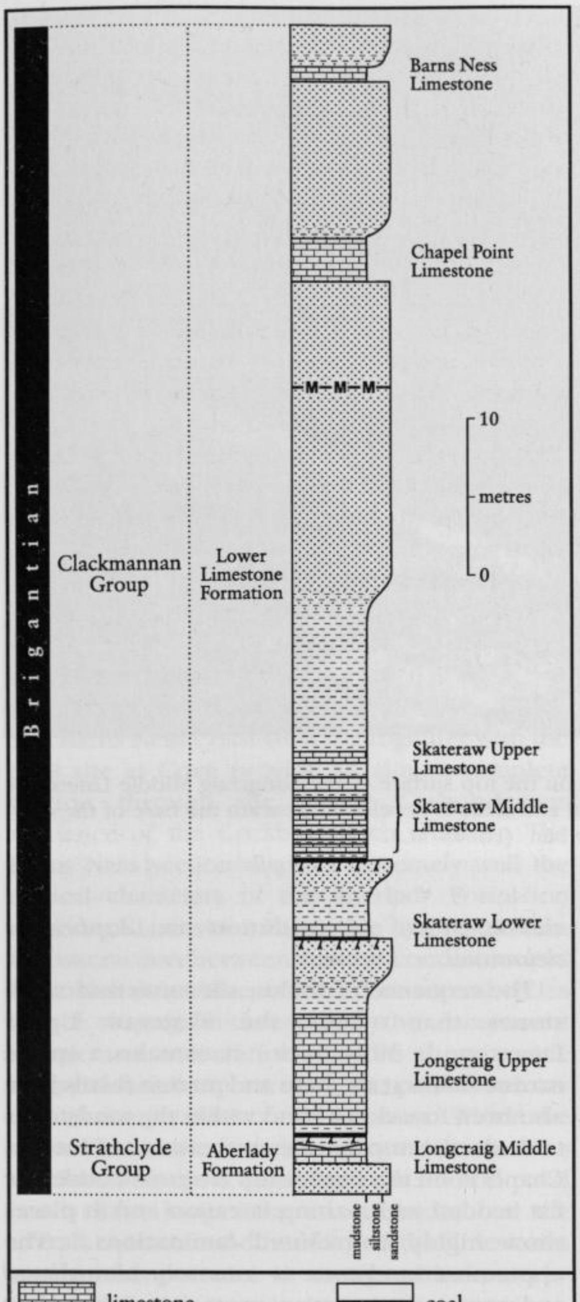


Figure 2.8 Simplified sedimentary log of the lower part of the Lower Limestone Formation (Brigantian) at the Barns Ness Coast GCR site. Based on various sources and including information from Davies *et al.* (1986).

development has been accompanied by a bleaching of part or all of the limestone to a creamy white colour and the lower limit of the bleached zone transgresses the bedding. The fluctuation in sea level that resulted in this superimposition of palaeosol features on a marine limestone was followed by renewed transgression and the development of a thin mudstone, rich in crinoidal debris, *Eomarginifera* and *Streblopteria*, which underlies the Longcraig Upper Limestone. This sequence, extending from the prominent potholed surface on the top of the Longcraig Middle Limestone to the base of the Longcraig Upper Limestone, is illustrated in Figure 2.9. The principal feature of the 6 m-thick Longcraig Upper Limestone is a coral band, composed almost entirely of *Koninckophyllum echinatum*, which lies about 1 m below its top. This band, known locally as 'Dunbar Marble' has in the past been exploited to a limited extent as a poor-quality ornamental stone. The limestone passes conformably up into a 5 m-thick mudrock and sandstone sequence in which the thinly bedded sandstones show ripple marks and trace fossils. Capped by a thin coal smut, these clastics are overlain by the 1 m-thick Skateraw Lower Limestone. The single post of this limestone has an abundance of gigantoproductids at the base and a few compound corals and bellerophontids towards the top. The clastic part of this cycle (3.8 m) consists of silty mudstone and silty sandstone rich in ironstone concretions passing up into soft grey fireclay with abundant *Stigmaria* on which lies a thin coal. The megaspores of this coal, and of the coal below the Longcraig Upper Limestone, were studied by Spinner (1969).

The overlying Skateraw Middle Limestone (5 m) is made up of a series of limestone beds separated by thin shale partings. The basal shale is thin and contains fusain fragments and marine fossils. Within the lower parts of the limestone there are gigantoproductid brachiopods and abundant *Zoophycos* traces. Chaetetid sponges are also common and occur in two forms: small, bun-shaped colonies and flat disc colonies. The latter invariably rest on and protect lensoid accumulations of fossil debris in which bioclasts are often coated by algae. In a band close to the top of the limestone the problematic fossil *Saccaminopsis fusulinaformis* occurs in abundance and above this there is a thin argillaceous

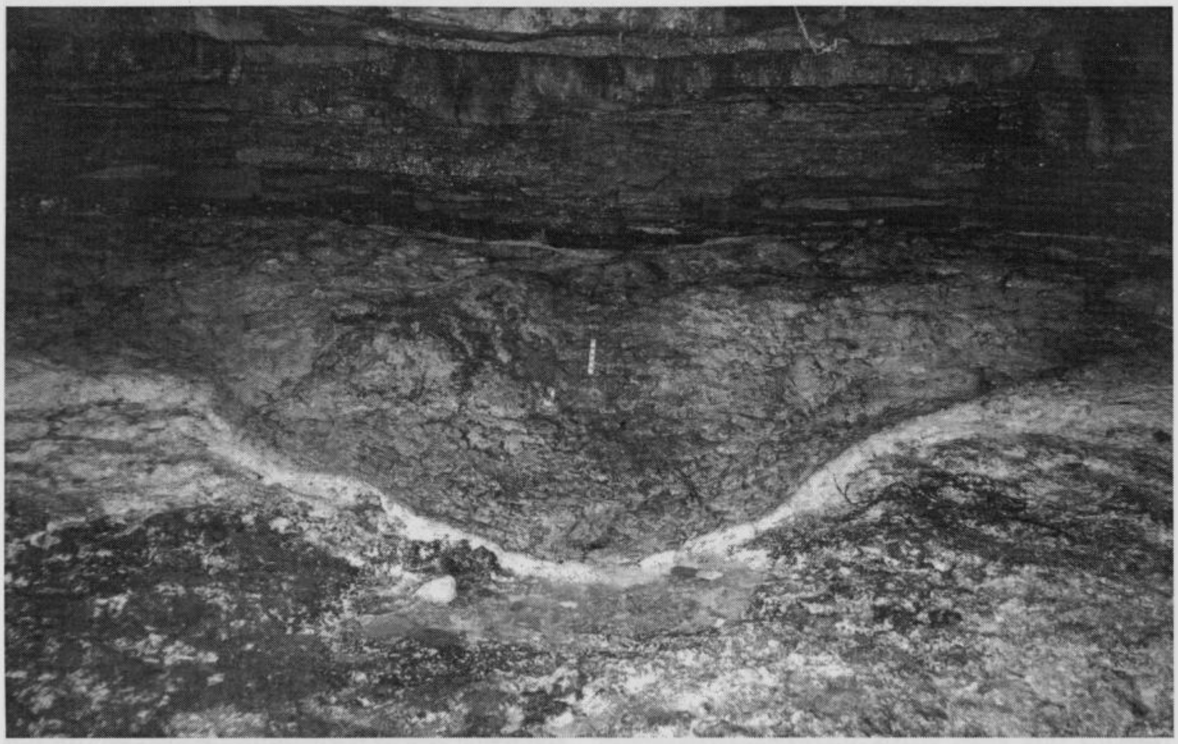


Figure 2.9 Palaeokarst solution hollow infilled by clay on the top surface of the Longcraig Middle Limestone at the Barns Ness Coast GCR site. Above this a thin coal and shale is developed beneath the base of the overlying Longcraig Upper Limestone. Note the 10 cm scale bar. (Photo: M.A. Whyte.)

band whose upper surface has scattered strews of echinoid plates, each patch representing the disturbed remnants of a single test. Clark (1960) has recorded a diverse conodont fauna from the Skateraw Middle Limestone and associated shales.

Immediately above the limestone at both Barns Ness and Skateraw there is a marine mudstone (1 m) and a thin sideritic limestone, the Skateraw Upper Limestone (0.4 m). In inland quarry exposures the equivalent beds are thicker and more variable and contain an extremely diverse marine fauna. Palaeoecological studies (Whyte, 1973) have indicated that they formed in a mud-bank complex and that the exposures within the site represent an off-bank facies. Although the bank facies is not represented here, similar facies occur at **Invertiel Quarry** (see GCR site report, this chapter). Skateraw is the type locality for the small blastoid *Astrocrinites bennei*, and for the juvenile productoids known as *Etheridgina complectens*, which occur attached to crinoid stems (Etheridge, 1876). Specimens from the shales at Catcraig were used by Carruthers (1910) in his classic study of evolution in *Zaphrentis delanouei*.

The sequence of shales, siltstones and sandstones that overlie the Skateraw Upper Limestone is 30 m thick. It contains a sparse marine fauna at the base and marine fossils have also been found in a band within the sandstones towards the top of the succession. Close to Chapel Point the sandstones are cross-bedded or flat bedded with parting lineation and in places show highly convoluted laminations. The uppermost sandstone is intensely bioturbated and contains stigmarian roots. At Barns Ness the equivalent beds appear to be siltier in nature.

The Chapel Point Limestone (2.8 m) sits directly on this sandstone and is a brown-weathering dolomitic limestone, which can be traced along strike from Barns Ness to Chapel Point. Features of the basal sandy crinoidal limestones have been described by Cain (1968), and crinoidal debris and *Zoophycos* traces are common throughout the limestone. Other fossil material is scarce but small colonies of *Siphonodendron* and large bellerophontids also occur. In the middle beds large chert nodules contain sponge spicules and other fine fossil debris. At Barns Ness the upper surface of the limestone is rich in valves of *Spirifer trigonalis* and spines of *Archaeocidaris urii*. Farther north, near Millstone Neuk, the top of the bed has in the past yielded complete specimens of *Archaeocidaris*.

About 12 m of strata occur above the Chapel Point Limestone and these are dominated by fine to coarse sandstones. Towards the top they include the Barns Ness Limestone, a sandy crinoidal limestone (1 m) which contains *Zoophycos* and which dies out on the foreshore north of Barns Ness. The equivalent of this unit is present north of White Sands, as a similar sandy limestone, but in a repeated exposure farther to the north it appears to be represented by a shale containing *Lingula* (Davies *et al*., 1986).

Interpretation

The Barns Ness Coast GCR site together with the GCR site at **Cove** provide an almost complete section through the Lower Carboniferous sequence of the Cockburnspath Outlier. The Barns Ness section displays extremely well the cyclical characters of the Aberlady Formation and Lower Limestone Formation that result from the interaction between marine conditions and fluvio-deltaic sedimentation. The several cycles are of varying thickness and the component marine and non-marine portions show a wide range of facies representing the palaeoenvironmental complexities of this situation. Within the marine intervals, faunal concentrations such as the *Saccaminopsis*, gigantoproductid and coral bands have long attracted attention, but the overall character and bedding of the limestones is also of importance in stratigraphical correlation and in palaeoenvironment interpretations. The marine mudrocks associated with the limestones also show significant faunal assemblages and those at the base of the Longcraig Upper Limestone and at the top of the Skateraw Middle Limestone are especially important. The varied clastic units within the fluvio-deltaic parts of the sequence show interesting sedimentary and trace-fossil assemblages and the range of palaeosols and thin coals is particularly significant. The well-developed palaeosol above the Longcraig Middle Limestone is particularly noteworthy.

The marine faunas within the sequence are typical of the Brigantian Stage and fragments of upper Brigantian (P_2) goniatites have been recorded from the mudrocks above the Skateraw Middle Limestone at localities about 1 km from the site (Currie, 1954). Palynological studies confirm this age, and in the Catcraig to Barns Ness section the NM–VF miospore zone boundary was placed within the mudrocks above the Skateraw Middle Limestone (Neves *et al*., 1973).

The thickness of the Barns Ness section is considerably less than that of equivalent sections elsewhere in eastern Scotland and northern England, but nevertheless it provides a vital link between the two areas. The Longcraig Upper Limestone appears to be the equivalent of the Hurlet Limestone at the base of the Lower Limestone Formation (Figure 2.4) and the disconformity represented by the palaeosol above the Longcraig Middle Limestone can be recognized in other sections, below the Hurlet Limestone, across the Midland Valley of Scotland. The Skateraw Middle Limestone is the equivalent of the Blackhall Limestone and the mudstones above the limestone contain distinctive elements of the Neilson Shell Bed Fauna (Whyte, 1973) which forms a useful guide assemblage for this interval (Wilson, 1966). Fragments of *Sudeticeras newtonense*, a P_2 goniatite, also occur in these mudrocks (Currie, 1954). The Skateraw Lower Limestone can be correlated with the Shields Bed horizon of the Midland Valley and though not stratigraphically diagnostic the correlative limestones at Aberlady and in East Fife are similar in thickness and in containing gigantoproductids. The correlation of the poorly fossiliferous Chapel Point Limestone and Barns Ness Limestone is less certain as this part of the sequence also differs in character from other areas and shows interesting internal lateral facies variations. However, the Barns Ness Limestone has been compared to the 'Hosie' Limestone of St Monance, which is a sandy crinoidal limestone rich in *Zoophycos*. When compared with sections in Northumberland there is a striking similarity between the Longcraig Upper Limestone and the Skateraw Middle Limestone and the Eelwell Limestone and Acre Limestone respectively (see **Spittal Shore** GCR site report, Chapter 3). The fauna of the mudrocks above the Acre Limestone includes species found at Barns Ness and Skateraw, including components of the Neilson Shell Bed Fauna.

Conclusions

The Barns Ness Coast GCR site is a key site providing a link between Dinantian sections in England and Scotland. It shows a nearly complete section of the Lower Limestone Formation (Brigantian) and the underlying topmost part of the Strathclyde Group. The section is only half the thickness of equivalent successions in the Lothians and Fife, and shows marine limestones, intervening clastics and well-displayed thin coals. This site is noteworthy for the occurrence of palaeokarstic surfaces (proving emergence and subaerial solution), coral biostromes, gigantoproductid brachiopod and *Saccaminopsis* bands, and megaspore-rich coals. The marine faunas are stratigraphically useful and have been the subject of detailed palaeoecological studies.

EAST SANDS–BUDDO NESS, FIFE (NT 519 158–NT 563 149)

Introduction

The East Sands–Buddo Ness GCR site is an elongate shore site, extending eastwards, from the eastern margin of St Andrews (NT 519 158), for a distance of 4 km along the East Fife coast to the Buddo Rock (NT 563 149). Within the site, which lies at the north-east extremity of the Carboniferous outcrop in the Midland Valley, are the local representatives of parts of the Anstruther, Pittenweem and Sandy Craig formations (Strathclyde Group, Asbian), which show significant differences from those formations in the Anstruther area. The succession was first described by Geikie (1902) and then parts of the section were described in detail by Kirk (1925) who, as corroborated by Forsyth and Chisholm (1977), first correctly established the sequence of marine bands. A guide to part of this site has been published by MacGregor (1968).

Description

The succession within the area is about 300 m thick and is dominated by sandstones and seatearths together with less significant developments of shale. The oldest rocks occur at the eastern end of the site and the youngest rocks towards the western end but, in the intervening ground, the rocks have been faulted and folded into a series of anticlines, synclines and domes (Figure 2.10) with the result that some beds are repeated several times along the section. In the past this caused problems of correlation at the site (Geikie, 1902; Kirk, 1925; Forsyth and Chisholm, 1977) but it also provides a useful insight into the variability of the succession, which contains evidence of local unconformities and of rapid changes in the thickness and character of particular units, including a cross-bedded shell bank (Kirk, 1925). At Buddo Ness there is a mudstone band with a marine fauna, which has been identified as the West Sands Marine Band and which is the local boundary between the Anstruther Formation and Pittenweem Formation. Close by and apparently below it stratigraphically are sandstones with non-marine dolomitic limestones. Between Kittocks Den (NO 554 151) and the Maiden Rock (NO 526 158) two principal marine bands have been recognized, of which the lower band has a more diverse fauna and is identified as the Witch Lake Marine Band (Forsyth and Chisholm, 1977), formerly known as the 'Encrinite Bed'. Leitch (1942) and Bennison (1961) have described unusual dwarfed specimens of the non-marine bivalve *Naiadites* from beds above the Witch Lake Marine Band near the Rock and Spindle. The upper marine horizon, which lies about 80 m higher, is identified as the St Andrews Castle Marine Band and marks the upper boundary of the Pittenweem Formation. The upper parts of the Pittenweem Formation at Pittenweem are cut out by a fault, and therefore this is the only good natural exposure of this part of the sequence in East Fife. The parts of the succession above the St Andrews Castle Marine Band are assigned to the Sandy Craig Formation. Within these beds there are concretionary calcretes, tuffaceous beds and a single marine band, the St Nicholas Marine Band.

Interpretation

The East Sands–Buddo Ness site is situated at the north-eastern extremity of the Carboniferous outcrop in the Midland Valley and thus provides invaluable palaeogeographical information. Compared with the equivalent succession at the **Elie–Anstruther** GCR site, the Strathclyde Group in the northern area is thinner and sandier. The marine bands present here can be

Figure 2.10 General view of the Craigduff Dome, a symmetrical fold structure in interbedded sandstones and mudstones of the Strathclyde Group at the East Sands–Buddo Ness GCR site, east of St Andrews. (Photo: British Geological Survey, No. D560, reproduced with the permission of the Director, British Geological Survey, © NERC, all rights reserved (IPR/19-39C).)

correlated with marine bands at Anstruther, but overall there are fewer marine intervals and their faunal content is reduced (Forsyth and Chisholm, 1977). Thus, as one goes north, the contribution of fluvio-deltaic material increases and marine influences wane. The development of calcrete (cornstone) palaeosols in the Sandy Craig Formation may indicate a period in which the climate was more arid than that during which the seatearths formed. A similar and probably coeval arid interval has been noted in successions in East Lothian (Andrews and Nabi, 1998) and indicates that this is a phenomenon of regional significance.

The section is dated by correlation with rocks elsewhere and is entirely Asbian in age. The marine bands are the local representatives of the MacGregor Marine Bands (Wilson, 1974, 1989). They are the oldest horizons in the Scottish Carboniferous succession to be correlatable over a considerable distance within the Midland Valley and they contain a distinctive fauna (Wilson, 1974). The section is also well known for its non-marine bivalve fauna (Geikie, 1902; Kirk, 1925; Leitch, 1942; Bennison, 1961; Brand, 1998).

Conclusions

This site reveals extensive and important sections of formations within the Strathclyde Group. These include northern developments of the Pittenweem Formation and the Sandy Craig Formation, in which the Witch Lake Marine Band (Encrinite Bed) and other associated beds with diverse marine faunas make their first appearance in the local succession. It is the only good natural exposure of the upper parts of the Pittenweem Formation in East Fife. When compared with sites to the south, it shows, in its attenuation with fewer marine bands and sandier beds, a markedly increased fluvio-deltaic influence. It also contains important non-marine faunas and pedogenic carbonates. The section is of crucial palaeogeographical and palaeoclimatic interest.

RANDERSTON COAST, FIFE (NO 608 118–NO 639 097)

Introduction

The Randerston Coast GCR site extends from Fife Ness (NO 639 097), 3 km north-east of Crail, north-west up the East Fife coast to Cambo Ness (NO 608 118), 4 km north of Crail. It includes the type locality of the Fife Ness Formation (Strathclyde Group) and beds belonging to the underlying Clyde Sandstone Formation (Inverclyde Group) and the overlying Anstruther Formation (Strathclyde Group). The site has long attracted the attention of geologists and provides a unique opportunity to examine successions of early Carboniferous (Tournaisian–?Holkerian) age in the north-eastern part of the Midland Valley. The sections have been described by Geikie (1902), who largely drew on the work of Kirkby (1880, 1901), and this work has been updated by Forsyth and Chisholm (1977). A guide to part of the area has been published by MacGregor (1968).

Description

The continuity of succession within the site is disrupted by faults, which divide the section up into a number of discrete areas, and give rise to gaps within the sequence and to some uncertainties as to the exact stratigraphical position of some parts of the sequence. The lowest beds in the succession belong to the Clyde Sandstone Formation (formerly the 'Balcomie Beds'), the base of which is not seen. They crop out to the north of Fife Ness (NO 631 102–NO 623 106) and consist of variegated mudstones and sandstones with conglomeratic layers and concretionary limestones and dolomites (Forsyth and Chisholm, 1977). Within the conglomeratic layers, clasts of lava and cementstone have been found (Forsyth and Chisholm, 1977; Browne, 1980b). The Clyde Sandstone Formation is conformably overlain by the basal 60 m of the Fife Ness Formation, which is 'characterized by the presence of white sandstones and the absence of coals and marine bands' (Forsyth and Chisholm, 1977). Grey and red mudstones also occur. A further 180 m assigned to higher parts of the Fife Ness Formation occur in the vicinity of Fife Ness. Near the base there are a number of dolomite bands containing algae, ostracodes, *Spirorbis* and fish remains (Forsyth and Chisholm, 1977). Fife Ness itself is formed of one particularly thick (23 m) sandstone with an erosive base.

The junction between the Fife Ness Formation and the Anstruther Formation is not exposed but strata believed to lie near the base of the Anstruther Formation are seen in a fault-bounded syncline (NO 621 107–NO 617 110). These beds, which are about 85 m thick, show cyclical sequences of sandstone, siltstone and shale. Although seatearths are well developed, coals are absent or poorly developed. Two marine bands, the Wormistone Marine Bands, contain molluscan faunas, and the lower band is particularly rich in gastropods (Geikie, 1902; Forsyth and Chisholm, 1977).

The remainder of the succession, which includes the well-known Randerston Limestones, is exposed in another fault-bounded tract within which the dominant structure is the Randerston Syncline (NO 616 112–NO 608 118). The succession has been recorded in detailed measured sections by Kirkby (1880, 1901; Geikie, 1902) who recognized and numbered in descending sequence 11 limestones. The section is about 130 m thick and is largely made up of cyclical sequences of sandstone, siltstone and shale with a few thin coals. Sandstones often show ripple cross-lamination, cross-bedding or convoluted bedding. The dolomitic limestones often contain a molluscan fauna which may be either marine or non-marine. Limestone VIII is rich in the non-marine bivalve *Paracarbonicola* while Limestone V contains marine forms such as *Schizodus*, *Sanguinolites*, *Naiadites*, orthoconic nautiloids and *Murchisonia*. Limestone VII is locally unique in containing the rhynchonellid brachiopod *Camarotoechia*. It also contains the bellerophontids *Bellerophon randerstonensis* and *Bucaniopsis undatus* (Weir, 1931) and other molluscs. Perhaps the best known limestone is Limestone IX, which contains algal balls and ostracodes. Within this red-coloured haematitic limestone (20 cm) the size of the algal balls increases upwards and in places towards the top they coalesce to form a stromatolitic layer (Figure 2.11). Bennison (1961) made a study of the dwarf specimens of *Naiadites* recorded by Leitch (1942) from the mudstone above Limestone IX and also described *Naiadites* and *Paracarbonicola* from above Limestone X (Bennison, 1960, 1961). Limestone X at Randerston is the type locality for *Paracarbonicola elegans*, which is the type

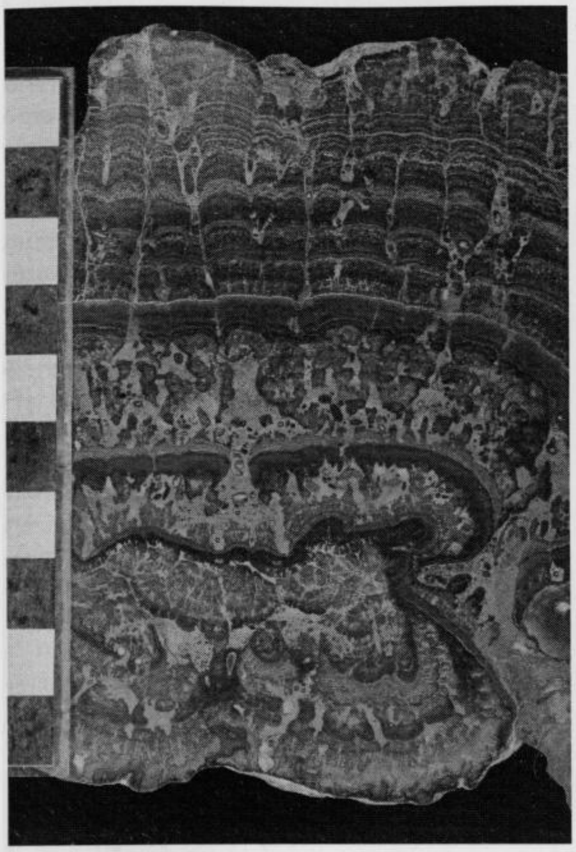


Figure 2.11 Limestone IX of the Randerston Limestones (Anstruther Formation, Strathclyde Group) showing the development of stromatolites from a large overturned oncoid. Note the 10 cm scale bar, divided into 1 cm intervals. (Photo: M.A. Whyte.)

species of its genus (Kirkby, 1880; Hind, 1894–1896; Bennison, 1960; Brand, 1998). These beds are all assigned to the Anstruther Formation.

Interpretation

The Randerston sections are unique and provide a record of changing environment conditions during the earliest parts of the Carboniferous Period in East Fife. The re-assignment of the Balcomie Beds to the Clyde Sandstone Formation (Browne *et al.*, 1999) follows Browne's (1980b) discussion of the characters of the Balcomie Beds and the significance of cementstone clasts, which may have been derived from the older Ballagan Formation. The Clyde Sandstone Formation appears to have been deposited in a braided fluviatile environment with overbank mudrocks and pedogenic carbonates indicating a semi-arid environment (Forsyth and Chisholm, 1977; Browne *et al.*, 1999). The lithological passage to the Fife Ness Formation may represent a change to a slightly less energetic fluvial and lacustrine environment and this continues up into the Anstruther Formation, which was deposited in thin cyclical units in lacustrine and fluvial environments in which enclosed shallow water bodies played an important role (Browne *et al.*, 1999). In contrast to the preceding formations, the deposits of the Anstruther Formation indicate that marine conditions occasionally penetrated into the area. The abundant but low-diversity marine and non-marine faunas and the dolomitic content of the Wormistone Marine Bands and the Randerston Limestones suggest that these formed in high-stress environments with variable or occasionally elevated salinity.

The stratigraphical position of the Randerston Limestones and their associated sequence presents an unresolved stratigraphical problem. These limestones are not known at outcrop anywhere else. Forsyth and Chisholm (1977) considered that they might be comparable in general character to the lower part of the sequence recorded in the Anstruther Borehole. However, palynological studies (Neves *et al.*, 1973) have indicated a correlation with the uppermost part of the Anstruther Formation. The chronostratigraphy of the succession is thus not fully established but it probably ranges from a Tournaisian to at least Holkerian age.

Conclusions

An important Lower Carboniferous (Tournaisian–Holkerian) aged succession with unique features occurs at the Randerston Coast GCR site in extensive coastal sections. Lower Strathclyde Group and upper Inverclyde Group strata, including the lower Anstruther Formation, the Fife Ness Formation and the Clyde Sandstone Formation, exhibit important and highly instructive facies changes of palaeoenvironmental, palaeoclimatic and palaeogeographical significance. The predominantly molluscan marine and non-marine faunas found at several levels throughout the section (Randerston Limestones and Wormistone Marine Bands) are the earliest fossil occurrences in the East Fife sequence and are not known elsewhere. The site is therefore significant in that it contains the earliest examples of non-marine bivalves in the Carboniferous

System of the UK. These faunas are the precursors of non-marine assemblages found in the Upper Carboniferous where they have proved particularly useful in stratigraphical correlation (see Cleal and Thomas, 1996). Furthermore, palynological (spore) studies carried out here provide controversial evidence of stratigraphical interest at this absolutely key Lower Carboniferous locality.

ELIE–ANSTRUTHER, FIFE (NT 481 996–NO 566 036)

Introduction

The Elie–Anstruther GCR site extends for 11 km from just west of Elie (NT 481 996) eastwards past St Monance to Anstruther (NO 566 036). It provides an almost unbroken sequence of Early Carboniferous (Asbian, Brigantian and basal Namurian) age and is the thickest known development (more than 2000 m) of Lower Carboniferous rocks in the Midland Valley. The first detailed account of these sections was by Brown (1860), and in the 1870s Kirkby made a careful detailed measured section of the sequence. This was incorporated in and first published in full in the memoir on *The Geology of Eastern Fife* (Geikie, 1902). A recent re-survey of the area led to the erection of a new lithostratigraphy for East Fife (Forsyth and Chisholm, 1977), and the name and type localities for components of the Strathclyde Group, namely the Pathhead, Sandy Craig, Pittenweem and Anstruther formations, all lie within the site. Sedimentological features from this section have been described by Greensmith (1961, 1965), Belt (1975), Fielding *et al*. (1988), Searl and Fallick (1990) and Kassi *et al*. (1998), while details of spore and trace-fossil assemblages have respectively been described by Neves *et al*. (1973) and Lees (1991). The site encloses within it the Ardross Castle GCR site described by Dineley and Metcalf (1999) in their GCR volume *Fossil Fishes of Great Britain*. An outcrop map showing the distribution of formations within the Strathclyde Group and the Clackmannan Group at this site is presented in Figure 2.12.

Description

The lowest beds in the sequence occur at the eastern end of the site where, between Anstruther (NO 566 036) and Cuniger Rock (NO 557 027), faulted successions of the Anstruther Formation outcrop (Forsyth and

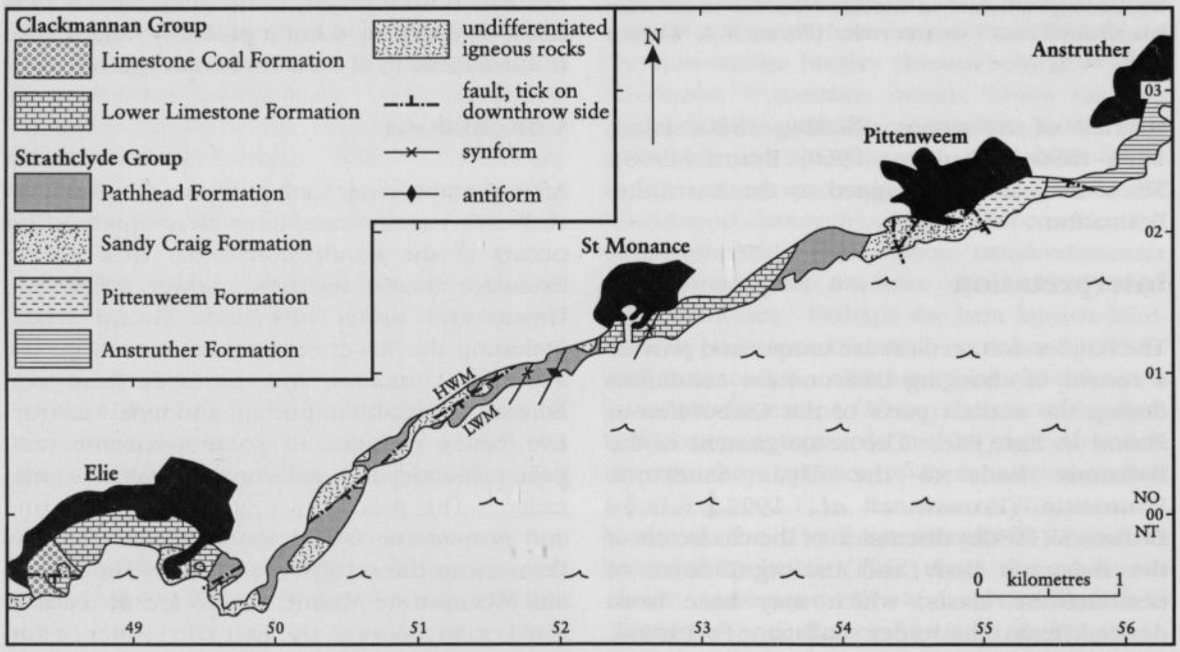


Figure 2.12 Simplified geological map of the foreshore area at the Elie–Anstruther GCR site showing the outcrop distribution of formations in the Strathclyde Group and Clackmannan Group. Based on various sources and including information from MacGregor (1968, 1996) and Forsyth and Chisholm (1977).

Chisholm, 1977). These beds consist of cyclical sequences of sandstone and grey mudstones and siltstones. Root beds, thin coals and dolomitic limestones also occur. Sandstones are generally thin and may be cross-bedded. There are, however, a few thicker sandstones, such as that which forms Johnny Dow's Pulpit. The mudrocks often contain non-marine faunas rich in ostracodes, fish remains, and the bivalves *Naiadites* and *Paracarbonicola*. A few marine intervals with molluscan faunas or *Lingula* have also been recognized and named. These include the Anstruther Wester Marine Band, the Billow Ness Marine Band, and the Chain Road Marine Band. Kassi *et al*. (1998) published an account of exposures in the Billow Ness area (NO 562 028).

The Anstruther Formation passes up conformably into the Pittenweem Formation, which is very similar in character to the Anstruther Formation in being made up of at least 220 m of cyclical alternations of thin sandstones, grey siltstones and mudstones, which often contain a non-marine fauna. Significant differences are that in the Pittenweem Formation dolomitic limestones are rare, oil shales are occasionally present, and marine faunas are more diverse, with the incoming of crinoids and brachiopods. Four marine bands have been recognized: the Cuniger Rock Marine Band, the Kirklatch Marine Band, the Pittenweem Marine Band and the Pittenweem Harbour Lingula Band (Forsyth and Chisholm, 1977). Non-marine bivalves from the Anstruther Formation and Pittenweem Formation have been described by Bennison (1960), and Brand (1998) has commented on the distribution of species of *Paracarbonicola*.

The junction between the Pittenweem Formation and the Sandy Craig Formation has been faulted out and the outcrops of the Sandy Craig Formation have also been affected by a number of faults. The formation is at least 550 m thick (Forsyth and Chisholm, 1977) and consists of variegated sandstones, siltstones and mudrocks. Thin beds of oil shale, non-marine limestone and dolomite occur, but are rarer than in the Pittenweem Formation, and there is only a single marine band, the Boat Harbour Marine Band. A distinctive feature of the formation is the occurrence of nodular pedogenic calcretes.

The overlying Pathhead Formation is about 300 m thick and crops out on the shore between Pittenweem and Pathhead near St Monance. The lithological characters of this unit are similar to those of the Pittenweem Formation and the succession is made up of alternations of grey mudstones and siltstones and thin sandstones. Coals and seatearths occur throughout. Although the base of the formation is defined by the West Braes Marine Band, marine bands become more common towards the top of the formation. Named horizons include the Ardross Limestones and Lingula Band, the Pathhead Marine Bands and the St Monance White Limestone. The top of the coral-rich St Monance White Limestone has been bleached and weathered penecontemporaneously and shows interesting lateral facies variations on either side of the St Monance Syncline (Macnair, 1917; Tait and Wright, 1923). Locally this unit appears to have been dolomitized (Figure 2.13). An interesting crinoid fauna has also been obtained from a lenticular band in the shales above the St Monance White Limestone on the western side of the St Monance Syncline (Tait and Wright, 1923; Wright, 1925, 1927, 1939, 1950–1960). Exposures of the Ardross Limestones and associated beds also recur on the west side of the syncline in the Ardross Castle area. A well-known and important feature of these outcrops is the 'shrimp band' below the Ardross Lower Limestone (Cater *et al*., 1989; Clark, 1989; Cusack and Williams, 1996; Williams and Cusak, 1997). There is also a bed containing small starfish (Spencer, 1914–1940), and Wright (1925, 1939, 1950–1960) has recorded a unique and distinctive crinoid assemblage from above the Ardross Limestones.

The Pathhead Formation is overlain by the Lower Limestone Formation (150 m), which is exposed within the core of the St Monance Syncline and consists of a series of Yoredale-type cycles in which the marine intervals are often well developed. The principal marine intervals are the St Monance Brecciated Limestone (3.5 m), the St Monance Little Limestone (0.6 m), which contains gigantoproductids, the Five Foot (or Charlestown Main) Limestone, and, towards the top of the formation, the variable group of Kinniny Limestones and associated Millhill and Seafield marine bands (Forsyth and Chisholm, 1977). Coal seams occur particularly in the strata below and above the Five Foot Limestone and are representative of thicker seams inland. The shales above the Five Foot Limestone contain representatives of the Neilson Shell Bed Fauna (Wilson, 1966; Forsyth and Chisholm, 1977). The record of the

Figure 2.13 Dolomitization of the St Monance White Limestone (Pathhead Formation, Strathclyde Group, Brigantian) close to St Monance, at the Elie–Anstruther GCR site, showing zone of dolomitization (darker band) between two paler developments of thinly bedded limestone with shale partings. (Photo: C. MacFadyen.)

goniatite *Sudeticeras* aff. *delépinei* from the Millhill Marine Band confirms the P_2 age of this interval (Wilson, 1980; Forsyth and Wilson, 1981) and helps to delimit the position of the P_2–E_1 boundary in Scotland. The Seafield Marine Band, which crops out by the St Monance Swimming Pool, contains a diverse marine fauna of brachiopods, molluscs and crinoids (Geikie, 1902; Wright, 1914a; Forsyth and Chisholm, 1977). This is the type locality for the trilobite *Paladin cuspidatus* (Reed, 1943; Osmólska, 1970). The sandstones above the Seafield Marine Band have been extensively bioturbated, and above these, mudrocks with a sparse marine fauna indicate the position of the Lower Kinniny Limestone. The sandstones and siltstones above the Lower Kinniny Limestone, which include a lenticular channel sandstone, have been variably bioturbated by the trace fossil *Teichichnus* (Chisholm, 1970). The Middle Kinniny Limestone is a distinctive finely crinoidal, dolomitic limestone with abundant traces of *Zoophycos*. The Upper Kinniny Limestone does not occur at St Monance but is found at Elie, where it is known as the 'Red Limestone' (Cumming, 1928). These exposures, which repeat the upper parts of the Lower Limestone Formation, also extend into the basal parts of the Limestone Coal Formation, consisting mainly of sandstones but including some coals (Cumming, 1928; Forsyth and Chisholm, 1977).

Interpretation

The extensive sequence at this site together with that at **Randerston Coast** (see GCR site report, this chapter) form a vital composite reference section from which to understand the complex and incompletely understood geology of East Fife. The Pittenweem Marine Band, formerly known as the 'Encrinite Bed', and some of the associated marine horizons of the Pittenweem Formation and the Sandy Craig Formation can for instance be traced northwards and used to elucidate the geology of the St Andrews area (Forsyth and Chisholm, 1977). However, within the St Andrews area the bands are fewer in number and less well developed. These marine bands belong to the MacGregor Marine Bands, which is the collective name for a very variable group of marine bands that can be widely detected in West Lothian, Fife, East Lothian and into northern England. These are the first extensive correlatable horizons within the Strathclyde Group and are of Asbian age. The higher marine bands of the Pathhead Formation and Lower Limestone Formation can be extensively correlated throughout the Midland Valley and are of Brigantian age (Wilson, 1989). The penecontemporaneous weathering of the St Monance White Limestone is comparable to the bleaching of the same horizon seen at Aberlady and Dunbar (Crampton, 1905, 1910; Tait and Wright, 1923) and at Corrie Burn (Macnair, 1917). The palynological zonation of Neves *et al.* (1973) could also facilitate correlation with other areas but problems in reconciling palynological and lithostratigraphical evidence (Forsyth and Chisholm, 1977) indicate that further work is required. The basal beds of the Limestone Coal Formation show a change in facies to one in which coals are better developed but marine limestones are absent.

Environmentally, the overall sequence represents a transgressive mega-sequence (Belt, 1975), with restricted lacustrine and lagoonal delta environments of the Anstruther Formation passing up through the Pittenweem Formation and Pathhead Formation, with increasing marine influence into the open marine–deltaic Yoredale cycles of the Lower Limestone Formation. The Sandy Craig Formation represents a departure from this trend and an extension of the delta to give a reduced marine influence. At this time and perhaps linked to the palaeogeographical changes, the climate also seems to have become more arid so that there is a recurrence of calcrete formation. Palaeogeographical changes with a reduction in marine influence also occur in the Limestone Coal Formation.

Conclusions

The Elie–Anstruther GCR site is a vital site for stratigraphical studies of Lower Carboniferous rocks in Scotland showing an almost complete Strathclyde Group to basal Limestone Coal Formation succession. The section is of national and international importance and includes the type sections of the upper Anstruther, Pittenweem, Sandy Craig and Pathhead formations. Excellent exposures of the Lower Limestone Formation and lower part of the Limestone Coal Formation are also present. In these formations a succession of faunas may be studied in their stratigraphical and palaeoenvironmental context. The site shows a remarkable range of both vertical and lateral facies variations and sedimentary structures, including penecontemporaneous limestone weathering. In addition, it shows a thicker succession than more northerly localities in Fife, with more marine bands present. It is a key Scottish Dinantian locality for palynological (spore) studies.

KINGHORN COAST, FIFE (NT 279 892–NT 272 869)

Introduction

The Kinghorn Coast GCR site lies on the coast of Fife between Kinghorn and Kirkcaldy (NT 279 892–NT 272 869). The exposed easterly dipping sequence is of Brigantian age and includes equivalents of the upper parts of the Strathclyde Group and of the Lower Limestone Formation. This classic site is the best exposure of rocks of this age in West Fife and at its base shows the interlayering of sedimentary rocks with the extrusive volcanic rocks of the Kinghorn Volcanic Formation (Bathgate Group). The section has been described by Geikie (1900), who provides a good critical appraisal of earlier work, and by Gordon (1914), Macnair (1917), Wright (1925), Allen and Knox (1934) and Francis (1961). Guides to the site have been published by Francis (in Mitchell *et al.*, 1960) and MacGregor (1968). The site overlaps with the Burntisland to Kinghorn Coast site described by Stephenson *et al.* (2003) in the *Carboniferous and Permian Igneous Rocks of Great Britain North of the Variscan Front* GCR volume, and the Abden site described by Dineley and Metcalf (1999) in the *Fossil Fishes of Great Britain* GCR volume, and is adjacent to the Pettycur site described by Cleal and Thomas (1995) in the *Palaeozoic Palaeobotany of Great Britain* GCR volume.

Description

The lower parts of the 130 m succession (Figure 2.14), close to Kinghorn, consist of interbedded lavas and sedimentary rocks, which belong respectively to the Kinghorn Volcanic Formation (Bathgate Group) and to the Pathhead Formation (Strathclyde Group, Brigantian). The lowest unit within the site is a quartzose

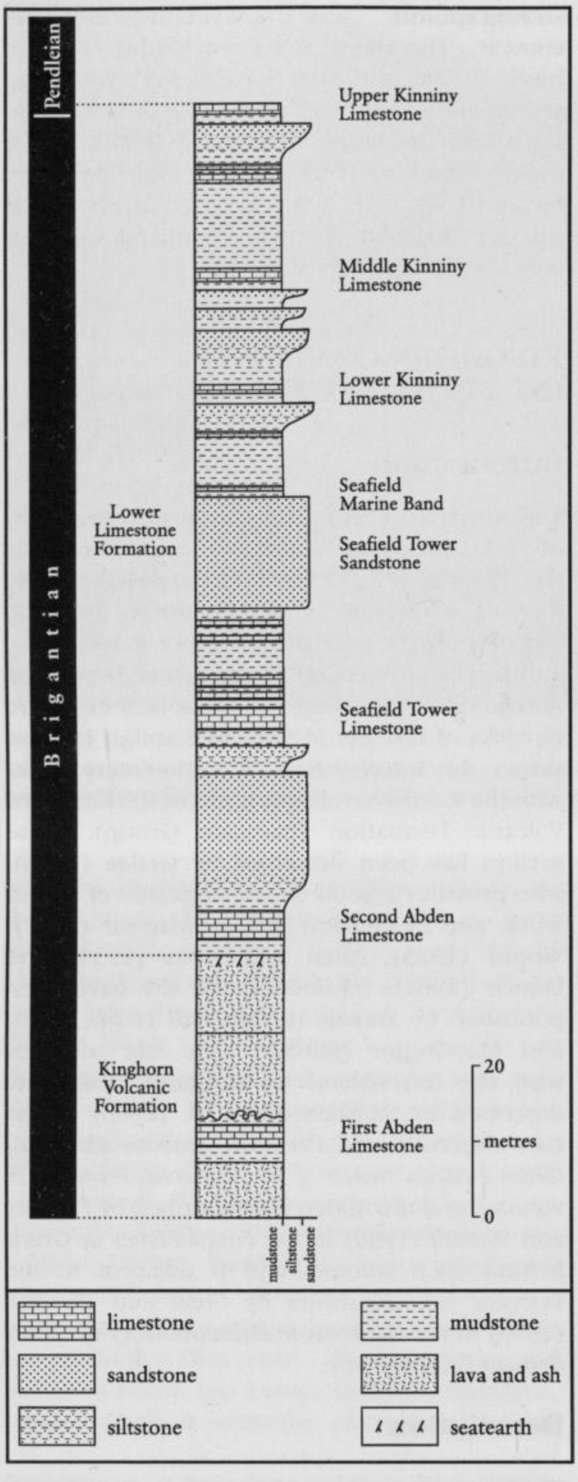


Figure 2.14 Simplified sedimentary log of the upper part of the Kinghorn Volcanic Formation and of the Lower Limestone Formation at the Kinghorn GCR site with intrusive igneous rocks omitted. After Francis (1961).

sandstone containing *Stigmaria*. Higher sedimentary intercalations within the volcanics are generally sandstones, siltstones and shales, which may be ashy and often contain plant remains (Geikie, 1900). Although some units, like the lowest bed, are palaeosols, others have been water-laid and display structures such as ripple marks. The highest intercalation includes the First Abden Limestone, which is a marine unit. In the shales at the base of this intercalation is the Abden Bone Bed, a unit separately scheduled for its fish fauna (Dineley and Metcalf, 1999), but which also contains plant remains, arthropod material and *Lingula*. The limestone (4 m) and the shales immediately above (20 cm) and below (10 cm) it have yielded a fairly diverse marine fauna including *Sanguinolites abdenensis*, *Actinopteria persulcata* and *Schizophoria resupinata*. The junction between the upper shale and the overlying basaltic lava is irregular and the lava appears to have flowed over and loaded into a soft sediment. This lava is the second highest lava within the volcanic sequence and is separated from the highest lava by a red bole.

The transition from the Kinghorn Volcanic Formation into the overlying beds of the Lower Limestone Formation is well seen on the foreshore to the north-east of Abden Home (Figure 2.15). The highest lava in the local sequence is overlain by tuffs (6 m), which pass up through a red bole into a green fireclay. The fireclay is capped by a thin (25 mm) ironstone band, which is rich in the bivalve *Naiadites crassa*. This is separated from the overlying Second Abden Limestone by 2.5 m of fossiliferous shale. The tuffs, fireclay and shales show a marked decrease in thickness northwards (MacGregor, 1968). The Second Abden Limestone (3.5 m) is crinoidal and bedded with argillaceous partings. Close to the base it contains large colonies of *Siphonodendron*, and higher in the limestone (2.1 m above the base) interambulacral plates of the echinoid *Archaeocidaris* are common.

Between the Second Abden Limestone and the Seafield Tower Limestone (= Charlestown Main Limestone) there are 26 m of sandstones and argillaceous sandstones into which has been intruded a teschenite sill. The Seafield Tower Limestone (3.5 m) is overlain by 14 m of calcareous shales and crinoidal limestone bands. These contain an abundant fauna of solitary

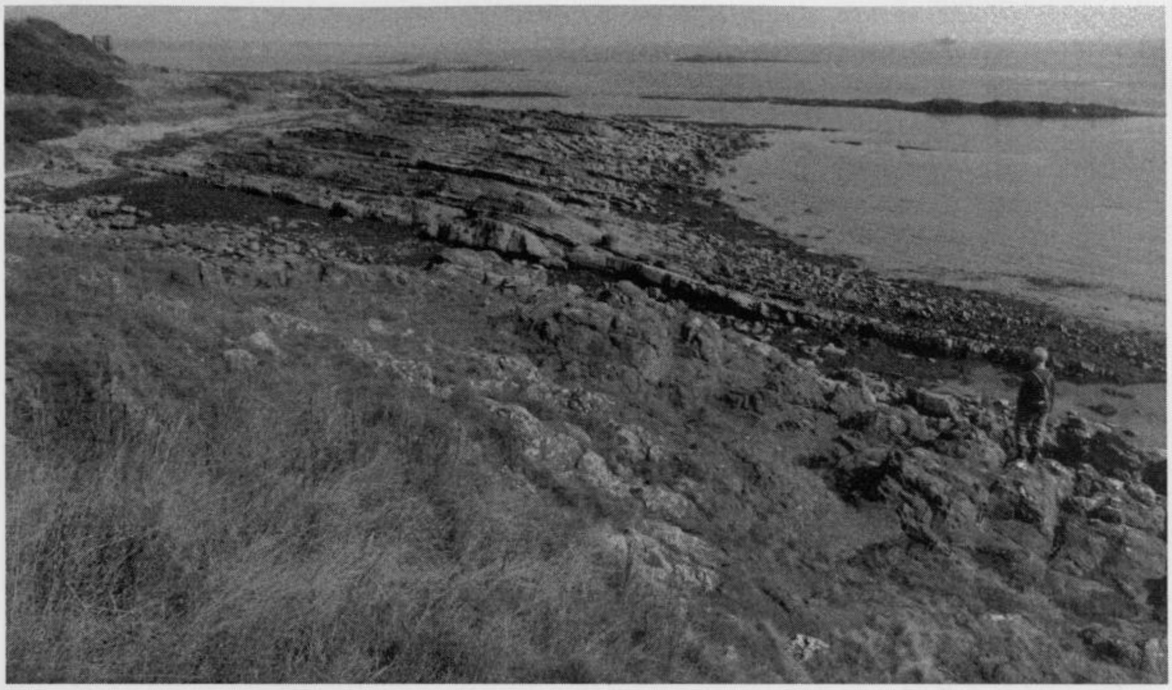


Figure 2.15 Exposure of the top of the Kinghorn Volcanic Formation (foreground) and overlying beds of the Lower Limestone Formation in the foreshore at the Kinghorn GCR site with the Second Abden Limestone in the middle distance. (Photo: British Geological Survey, No. D5227, reproduced with the permission of the Director, British Geological Survey, © NERC, all rights reserved (IPR/19-39C).)

and compound rugose corals (zaphrentids and *Siphonodendron*), brachiopods (productoids, gigantoproductids, *Schizophoria*, *Cleiothyridina*, spiriferoids), gastropods (*Pseudozygopleura*, *Straparollus*), nautiloids, echinoids (*Archaeocidaris*) and crinoids (*Parazeacrinites*, *Phanocrinus*, *Ureocrinus*, *Onychocrinus*, *Platycrinites*). The shales are overlain by a thick (16 m) cross-bedded sandstone (Seafield Tower Sandstone) on the outcrop of which Seafield Tower has been built.

The succession above the thick sandstone is 60 m thick and is a variable and cyclical sequence of limestones, shales, siltstones and sandstones (Wright, 1925; Allen and Knox, 1934; Francis, 1961). Four marine intervals have been distinguished. These are the Seafield Marine Band and the Kinniny Limestones (Lower, Middle and Upper) (Allen and Knox, 1934; Francis, 1961). The Lower Kinniny Limestone contains algal masses (MacGregor, 1968) but the Middle Kinniny Limestone is the most fossiliferous. The Upper Kinniny Limestone marks the top of the Lower Limestone Formation.

Interpretation

The Kinghorn Coast GCR site shows instructively the relationship between volcanism and sedimentation and the encroachment of marine deposition onto the volcanic pile of the Kinghorn Volcanic Formation. The quartzite near the base is of historical importance as in the past it 'attracted attention during the famous controversy between the Neptunists and Plutonists' (Geikie, 1900). Although the correlation of the First Abden Limestone and Second Abden Limestone is still uncertain, the occurrence of the P_2 goniatite *Sudeticeras* aff. *newtonense* in a laterally equivalent section (Currie, 1954; and see **Roscobie Quarry** GCR site report, this chapter) indicates that the upper parts of the succession, above and including the Seafield Tower Limestone, are of uppermost Brigantian age (George *et al.*, 1976; Browne and Woodhall, 1999). Compared with equivalent sections in East Fife, the succession of these beds is thinner and coals are absent or thinner. Conversely, the Seafield Tower Limestone is considerably thicker than its equivalent in the St Monance area. These differences reflect the site's depositional position on the relatively positive feature of the Burntisland High.

The shales below the First Abden Limestone contain a sequence of faunal assemblages, which were collectively studied by Macnair (1917), and became known as the 'Abden Fauna' but are now referred to as the 'Macnair Fauna' (Wilson, 1989). This fauna has been a major consideration in debates about the correlation of beds at the top of the Strathclyde Group and the base of the Lower Limestone Formation (Macnair, 1917; Wilson, 1979, 1989; Whyte, 1981). Macnair (1917) considered that this faunal succession, which included a basal fish layer, was characteristic of the Hurlet Limestone horizon and used it as a guide to correlation throughout the Midland Valley. However, elements of the Macnair Fauna, including the bone bed, can be found at other horizons and, in the unusual Kinghorn succession, it is not clear whether the First Abden Limestone or the Second Abden Limestone or even both is the equivalent of the Hurlet Limestone (Wilson, 1989). Irrespective of which limestone correlates with the Hurlet Limestone and marks the local base of the Lower Limestone Formation, the lower part of the succession belongs to the Strathclyde Group and is probably all of early Brigantian (P_1) age.

The fauna of the shales that underlie the Second Abden Limestone were the subject of a major and innovative palaeoecological study by Ferguson (1962, 1963). Within the transgressive shale sequence, four successive topozones were recognized, from a low-diversity *Lingula* and *Streblopteria* dominated assemblage towards the base, to an *Eomarginifera*, coral and bryozoan community at the top (Ferguson, 1962).

The taxonomy of the crinoid fauna of the Seafield Tower Limestone was extensively studied by Wright (1912, 1914b, 1920, 1925, 1939, 1950–1960) and although generally similar in character and composition to the faunas of **Invertiel Quarry** and **Roscobie Quarry** (see GCR site reports, this chapter), the site has provided type and figured material for a number of species. Wright (1926, 1927) included material from Seafield in his pioneering studies of variation in the cups of *Parazeacrinites konincki*, *Ureocrinus bockshii* and *Phanocrinus calyx*.

The four marine horizons above the Seafield Tower Limestone have been named and correlated with successions elsewhere in Central and West Fife (Allen and Knox, 1934; Francis, 1961). They form an important reference section for these beds (Wilson, 1989) and in the correlations between West and East Fife (Forsyth and Chisholm, 1977) and between Fife and both the Central Coalfield and the Lothians (Wilson, 1989).

Conclusions

The Kinghorn Coast GCR site is one of the key Dinantian (Brigantian) sites in the Midland Valley of Scotland. It is historically noteworthy and 'is not only one of the most continuous but also one of the most interesting in the East of Scotland' (Macnair, 1917). The site is extremely important in showing Strathclyde Group and Lower Limestone Formation strata interbedded with, and overlying, lavas of the Kinghorn Volcanic Formation (Bathgate Group). In addition, it shows important contrasts with sections elsewhere in its stratigraphical make-up and relative proportions of different lithologies. The shales adjacent to the Seafield Tower Limestone and the First Abden Limestone and Second Abden Limestone are all highly fossiliferous, and have been the subject of detailed palaeontological and palaeoecological studies.

INVERTIEL QUARRY, FIFE (NT 272 898)

Introduction

The Invertiel Quarry GCR site is a disused quarry (NT 272 898), which lies just within the burgh boundary of Kirkcaldy and about 4 km from the town centre. It is one of the premier palaeontological sites in Britain and an internationally significant site for Brigantian (Lower Carboniferous) crinoids. The quarry has been described by Geikie (1900) and Wright (1912, 1914b, 1920).

Description

The site provides a highly fossiliferous section through part of the Lower Limestone Formation (upper Brigantian). At the base, an 8 m-thick sequence of light-grey, bedded limestone (the Charlestown Main Limestone) is overlain by a complex of lenticular limestones, argillaceous limestones and mudrocks, up to 10 m thick

(Figure 2.16). This in turn is sharply overlain by a thick cross-bedded sandstone (10 m) with plant fragments, which was also worked as a source of stone (Allen and Knox, 1934). Within the lenticular units immediately above the limestone, Wright (1912) distinguished three argillaceous units, which he labelled in ascending sequence as beds 1, 2 and 3. Other units within the complex were not, however, separately designated.

Bed 1 (1 m), which lay immediately above the Charlestown Main Limestone, has revealed the most diverse fauna including foraminifera, sponges, zaphrentid corals, *Heterophyllia*, ostracodes, productoid and other brachiopods, fenestellid bryozoans, bivalves (*Sanguinolites*, *Cypricardella*), gastropods (*Pseudozygopleura*), orthoconic and cyrtoconic cephalopods, *Archaeocidaris* and abundant crinoid remains (Wright, 1912). The principal crinoids were *Platycrinites* spp., *Parazeacrinites konincki*, *Phanocrinus calyx* and *Ureocrinus bockshii*. Bed 1 is capped by 0.75 m of crinoidal limestone. The dark calcareous shales with interbedded carbonate lenticles and nodules (6 m), which make up Bed 2, contain a fauna similar to that of Bed 1, although this diminishes in abundance as the bed is traced southwards within the quarry (Wright, 1912). A lenticular limestone (0.2–0.7 m) separated Bed 2 from Bed 3. This dark mudrock (1 m) contains a varied fauna in which crinoids are less abundant. However, in contrast to beds 1 and 2 from which only cups were recorded, rare examples of complete crowns were recorded from Bed 3 (Wright, 1912). The site has been used for land-fill and only the top of the Charlestown Main Limestone, parts of the overlying mudrock and limestone complex, and the basal parts of the sandstone can now be seen within the site boundary.

Interpretation

The principal interest in the Invertiel Quarry GCR site lies in the complex of beds 1, 2 and 3 (Wright, 1912). However, the relationship of these beds to the underlying limestone and to the overlying sandstone are also important and places them within a stratigraphical and palaeoenvironmental context. The Charlestown Main Limestone is the principal limestone in the

Figure 2.16 Exposure of the Charlestown Main Limestone (Lower Limestone Formation, Upper Brigantian) at the Invertiel Quarry GCR site. (Photo: C. MacFadyen.)

middle of the Lower Limestone Formation of West Fife (Allen and Knox, 1934) and is the local equivalent of the Blackhall Limestone of the Glasgow area (upper Brigantian, P_2; see Figure 1.4, Chapter 1, and Figure 2.4). The sandstone is the equivalent of the Seafield Tower Sandstone, which is well displayed in the **Kinghorn Coast** GCR site (Allen and Knox, 1934).

The character and fauna of the beds between the Charlestown Main Limestone and the sandstone indicates that they represent parts of small bank features similar to those described from the Dunbar area (Whyte, 1973). These banks, which are unique to the beds above the Charlestown Main Limestone and equivalent limestones in eastern Scotland, are typified by being argillaceous accumulations with a high bioclastic content and a diverse fauna among which crinoids are usually prominent. They contrast with the carbonate banks also found within the Charlestown Main Limestone at localities such as **Roscobie Quarry** (see GCR site report, this chapter). The crinoid fauna of Invertiel Quarry, and particularly from beds 1, 2 and 3, was studied assiduously by Wright over a period of more than 40 years; as well as producing a large number of papers, the taxonomic results of his studies were included within his two major monographs (Wright, 1939, 1950–1960).

Some 39 species of crinoids, equivalent to half the total number of crinoid species known from the Scottish Carboniferous succession, have been recorded from Invertiel Quarry. For 25 of these species the type material comes from, or includes specimens from, Invertiel Quarry and for a further five species specimens from Invertiel were figured by Wright (1950–1960). The fauna, which includes 26 species of inadunate crinoids, seven species of flexible crinoids and six species of camerate crinoids, shows rheophobic tendencies and completely lacks rheophilic camerates of the type that occur in the Clitheroe 'knoll reef' crinoid assemblages (see Chapter 6). Although most of Wright's work was essentially taxonomic in character, his studies of variation in the anal (CD) plate inter-ray of *Parazeacrinites*, *Ureocrinous* and *Phanocrinus*, which were in large part based on his large collections from Invertiel Quarry, were innovative and demonstrate his understanding of evolution and the species concept (Wright, 1926, 1927).

The non-crinoid fauna of the 'Beds' is also diverse (Geikie, 1900; Reed, 1943, 1954) and includes foraminifera, sponges, tabulate and both solitary and compound rugose corals, annelid tubes, ostracodes, trilobites, bryozoans, brachiopods, bivalves, gastropods, coiled and orthoconic cephalopods, blastoids, echinoids and a variety of fish teeth. Brachiopods and trilobites from Invertiel have been described and figured by Reed (1943, 1954) and Osmólska (1970).

Conclusions

The Invertiel Quarry GCR site exhibits a thick development of the Lower Carboniferous Charlestown Main Limestone (Lower Limestone Formation, upper Brigantian). The fauna of the overlying shales and limestones is extremely diverse, including corals, brachiopods, sponges, molluscs, bryozoans and echinoderms. The site is particularly noted for its crinoids and has yielded type and figured specimens for a large number of crinoid species.

KINNESSWOOD, PERTH AND KINROSS (NT 181 036)

Introduction

The Kinnesswood GCR site consists of a section in the gully of Kinnesswood Row (Figure 2.17), on the western flank of Bishop Hill (NT 181 036) and 6 km east of Kinross. It lies towards the northern edge of the main Carboniferous outcrop within the Midland Valley. It provides a classic section through the problematic Kinnesswood Formation (Inverclyde Group, Fammenian to Tournaisian) across a regionally significant disconformity and into the Pathhead Formation (Strathclyde Group, Brigantian) and local equivalent of the Charlestown Station Limestone (Lower Limestone Formation, Brigantian). It thus provides important insights into the palaeogeographical complexities of the Midland Valley Basin. MacGregor (1968) has provided the best account of the site though useful information is also given by Chisholm and Dean (1974).

Description

The rock sequence within the Kinnesswood GCR site dips very slightly to the east so that as one ascends the gully of Kinnesswood Row one

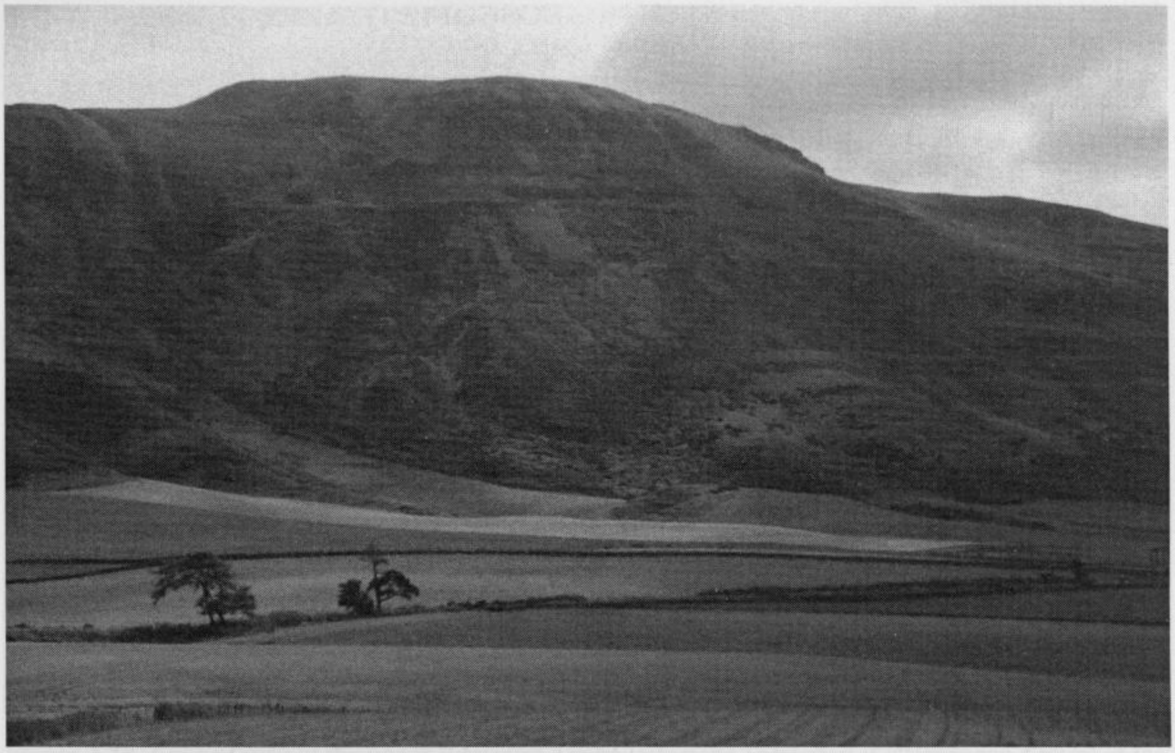


Figure 2.17 View of Bishop Hill from the north showing the prominent gully of Kinnesswood Row in which the Kinnesswood Formation (Inverclyde Group, Tournaisian) and Pathhead Formation (Strathclyde Group, Brigantian) are exposed. (Photo: M.A. Whyte.)

ascends the sequence. The site displays a thin development of Lower Carboniferous rocks resting on red sandstones and calcretes belonging to the Kinnesswood Formation (Inverclyde Group). This is the name locality and type section for the Kinnesswood Formation, which is here about 40 m thick. The formation consists largely of white-, yellow- or brown-coloured sandstones with thinner bands of siltstone and mudstone. Some of the coarser-grained sandstones are lenticular with erosive bases and large-scale trough cross-bedding whereas the fine- to medium-grained sandstones are poorly bedded or massive. Current directions from these cross-stratified beds indicate flows from the west. In places, fining-upward sequences can be recognized in which erosively based coarse sandstone grade upwards through finer sandstone into siltstone and mudstone. The sandstones are locally cemented with dolomite. The occurrence of probable pedogenic nodular dolomite concretions in these beds is characteristic of the formation. Fragments of these concretions are common in the coarser sandstones resting on erosion surfaces and show that the concretionary carbonates developed penecontemporaneously within the original sediments. The highest bed of the Kinnesswood Formation is a sandy calcrete (1.6 m). The overlying Carboniferous sequence (33.5 m) is made up of shales and siltstones with a few sandstone bands. In addition there are two coal seams and two limestone bands. The lower coal (15 cm) lies almost immediately on the calcrete. *Lingula* has been recorded from one of the dark shales. The upper limestone is about 3 m thick and both it and an underlying shale (7 m) contain crushed marine fossils including brachiopods and bivalves.

Interpretation

The Kinnesswood Formation is of uncertain Devono–Carboniferous age although miospore evidence from New Cummnock (Browne *et al.*, 1999) suggests that it is probably largely of early Carboniferous (Tournaisian) age. It is interpreted as having formed in a fluviatile environment with river systems flowing off a rejuvenated upland to the north-west (Chisholm and Dean, 1974). The occurrence of calcrete palaeosols indicates a semi-arid environment. At Kinnesswood the formation has a reduced thickness due to intra-Carboniferous erosion, which has removed the upper parts of the sequence (Chisholm and Dean, 1974; Browne *et al.*, 1999). This erosion surface can be followed along the outcrop from the Lomond Hills area eastwards into Stratheden (Chisholm and Dean, 1974).

The upper limestone is equated with the Charlestown Station Limestone (MacGregor, 1968), which lies at the base of the Lower Limestone Formation (upper Brigantian, P_2). The strata that lie between the top calcrete of the Kinnesswood Formation and the Charlestown Station Limestone horizon probably represent the local equivalents of the upper parts of the Pathhead Formation, which are also late Brigantian in age, and confirmatory miospore evidence for this has been obtained from the coal near the base of the sequence (Browne, 1980b). Thus although no discordance in dip can be detected between the Kinnesswood Formation and the overlying strata, a very considerable gap in deposition is indicated during which over 2000 m of strata were deposited in East Fife (Forsyth and Chisholm, 1977). Elsewhere within the Stirlingshire, Kinross and Fife area the extent of the discordance appears to be less (Chisholm and Dean, 1974) and the relationship at Kinnesswood may reflect its position on a northerly extension of the Burntisland High. The beds of the Pathhead Formation appear to have formed in a distal deltaic environment and the presence of coals indicates a warm but humid climate.

Conclusions

The Kinnesswood GCR site is a unique site showing a regionally important unconformity between undoubted Lower Carboniferous strata and rocks of less certain Devono–Carboniferous age. Beds of the Pathhead Formation (Strathclyde Group) containing thin marine intervals rest with marked overstep on the type section of the Kinnesswood Formation (Inverclyde Group). Thus here there is evidence of a much less complete Lower Carboniferous rock succession than that proved in more easterly and southerly parts of the Midland Valley.

ROSCOBIE QUARRY, FIFE (NT 091 932)

Introduction

The Roscobie Quarry GCR site, a disused quarry in the Charlestown Main Limestone (Lower Limestone Formation, upper Brigantian), lies 5 km north of Dunfermline in West Fife (NT 091 932). Geikie (1900) described the quarry briefly and gave a faunal list, but the best descriptions of the quarry, at the time when it was being worked, are those of Wright (1914b, 1920). The site is of great palaeontological importance and in particular Wright (1914b, 1920, 1939, 1950–1960) worked extensively on its significant crinoid fauna. Roscobie Quarry also has the best exemplars of the unusual carbonate bioherms that occur in the Charlestown Main Limestone of West and Central Fife. Detailed sedimentological studies of these carbonates have recently been carried out by Pickard (1992, 1994).

Description

The most important and best known section at Roscobie is its north-eastern quarry face; now the only part of the original quarry remaining and protected after a period of landfill. In this face a 30 m-thick sequence of the Charlestown Main Limestone (13 m) and overlying shale (13 m) and sandstone (4 m) can be seen (Figure 2.18). The basal beds of the Charlestown Main Limestone comprise biomicrites (2 m), containing gigantoproductids, and crinoid debris. These are overlain by bedded biomicrites and biomicrosparites, which can be seen at the north end of the section and which pass laterally into a thicker and more massive lenticular unit (the 'hump' or knoll of Wright, 1920) of crinoidal biomicrites (wackestones and packstones), which becomes coarser and more crinoidal towards the top. The sedimentology and palaeoecology of these beds have been described in detail by Pickard (1990, 1992, 1994). Within them, brachiopods, sponge spicules and bryozoan and crinoidal debris are abundant, and foraminifera, worm tubes, ostracodes and calcispheres are common. Microfabrics and '*stromatactis*-like' cavities within the limestones suggest a significant microbial contribution to the carbonates (Pickard, 1992, 1993, 1994; Friedman, 1993). Thickness variations in the limestones have

Figure 2.18 General view of the upper Brigantian Lower Limestone Formation (Clackmannan Group) at the Roscobie Quarry GCR site, illustrating massive lenticular limestone units of a carbonate buildup within the Charlestown Main Limestone (base of cliff face) overlain by shales and sandstones (middle and top of cliff face). (Photo: C. MacFadyen.)

caused compactional shears and slickensiding both in the limestone and in the overlying shales. These dark shales contain a prolific and diverse marine fauna, especially at their base.

Interpretation

The limestone at Roscobie Quarry is the Charlestown Main Limestone of West Fife, which is the equivalent of the Blackhall Limestone (middle Lower Limestone Formation) and is of late Brigantian (P_2) age. The site provides a unique opportunity to study the transition from level-bedded limestones into a biohermal carbonate buildup, which had developed a small relief above the surrounding sea floor (Pickard, 1992). A reconstruction has determined that the buildup must have been at least 230 m long, 46 m wide and 15 m thick, and that following its initial development as small lenticular banks its subsequent growth was predominately vertical (Pickard, 1992). This led to steep palaeoslopes of up to 30° against which flanking debris beds were deposited during erosional phases. The Roscobie complex appears to have developed in deeper water than similar buildups nearby at Charlestown and Kinnesswood (Bishop Hill) (Pickard, 1992). In the Midland Valley, carbonate buildups of this type are rarely exposed and are restricted in their occurrence (Pickard, 1994). Those of the Charlestown Main Limestone in West Fife have been linked to an area of reduced subsidence on the structural feature known as the 'Burntisland High' (Pickard, 1992, 1994). The buildup facies may once have been more widespread in association with structural highs and largely lost as the limestones were eroded off the highs in later geological periods. The carbonate of Roscobie Quarry contrasts in character with the more argillaceous banks, which occur in the calcareous shales above the Charlestown Main Limestone at **Invertiel Quarry** (see GCR site report, this chapter) and also in East Lothian (Whyte, 1973). Growth of the bioherm and deposition of limestone was terminated by the influx of the overlying mud.

Most of the previous work on Roscobie Quarry has been taxonomic in nature and in particular has concentrated on the crinoid fauna for which the site has become internationally famous (Wright, 1914b, 1920, 1939, 1950–1960). This material largely came not from the limestone itself but from the calcareous basal parts of the overlying dark shale. Although the crinoid fauna is not quite as abundant or as diverse as that at **Invertiel Quarry**, it is better preserved, and fine crowns including good specimens of *Woodocrinus* and *Poteriocrinites* have been obtained. The locality has provided type or figured material for 21 of the 27 crinoid species that have been recorded from it. In composition, the fauna shows rheophobic tendencies and is very different both taxonomically and ecologically from 'knoll reef' faunas of the English Carboniferous System. Wright (1926, 1927) used specimens from Roscobie in his ground-breaking studies of the variation of the anal (CD) plate inter-ray in several inadunate crinoid species.

The fossil list for other groups is also long (Geikie, 1900) and includes a number of species for which this is the type locality. These include sponges, trilobites, bivalves, gastropods and brachiopods (Hinde, 1887–1912; Hind, 1896–1905; Reed, 1943, 1954). In addition to the new species *Bucaniopsis roscobiensis*, Weir (1931) recorded *B. decussatus*, *B. striatus* and *B. tenuis* from Roscobie Quarry. This diversity of bellerophontid gastropod species is a typical feature of the Neilson Shell Bed Fauna (Weir, 1931; Wilson, 1966) and this fauna is represented in the shales above the Charlestown Main Limestone at Roscobie Quarry. This supports the correlation of the Charlestown Main Limestone with the Blackhall Limestone of the Central Coalfield Basin. Currie (1954) recorded varieties of the goniatite *Beyrichoceratoides truncatum* from Roscobie and more importantly *Sudeticeras* aff. *newtonense* which confirms the P_2 age of the Charlestown Main Limestone (see Riley, 1993; and **Kinghorn Coast** GCR site report, this chapter).

Conclusions

The Roscobie Quarry GCR site reveals an outstanding section of the biohermal Charlestown Main Limestone (Lower Limestone Formation, upper Brigantian) and of the fossiliferous shale and sandstone sequence immediately above it. This is a classic locality, famous for its crinoid fauna, but yielding an abundance of other taxa of great taxonomic, palaeoecological and stratigraphical interest. In addition to its fauna, the site exhibits sedimentological features of major significance, including the transition from bedded limestone into the massive limestones of a carbonate buildup within the Charlestown Main Limestone.

QUEENSFERRY SHORE, CITY OF EDINBURGH (NT 132 784–NT 142 785)

Introduction

The Queensferry Shore GCR site consists of the foreshore exposures on the south side of the Firth of Forth and on either side of the Forth Railway Bridge (NT 132 784–NT 142 785). These contain a more-or-less complete section through the middle part of the West Lothian Oil-Shale Formation (Strathclyde Group) and are of Asbian age. The sequence, which is exposed on the westerly dipping east limb of a syncline, has been described in detail by Peach *et al.* (1910) and Carruthers *et al.* (1927). Guides to the succession have been published by Tulloch (in Mitchell *et al.*, 1960), MacGregor (1968), Tulloch *et al.* (1971) and McAdam (in McAdam and Clarkson, 1986).

Description

The lowest beds in the sequence comprise mudstones with cementstones and thin oil shales, including the Dalmahoy Oil Shale, and are exposed at the eastern end of the section. Above this, mudrocks (9 m) include the two prominent cementstones known as the 'Queensferry Cements'. The lower Queensferry Cement is yellowy buff in colour and is noted for its oil-filled cavities (McAdam in McAdam and Clarkson, 1986). The upper Queensferry Cement is oolitic. The Pumpherston Shell Bed, which is rich in thin-shelled bivalves, gastropods, *Lingula* and orthoconic cephalopods, lies about 1 m higher. This shell bed forms the base to a 25 m-thick succession of dark shales and oil shales, which are known as the 'Pumpherston Oil Shale'. The shales contain cementstone and ironstone bands, phosphatic coprolites, fish remains and, close to the top, a band with *Naiadites* and *Euestheria*. Capping this locally, and seen here at the high-water mark, is a unit of sandstone and dolomitic limestones. These contain desiccation structures and, at the top, laminated domes of stromatolitic algal limestones (Figure 2.19). These beds, known as the 'Bogwood Limestone', have been described in detail by Maddox and Andrews (1987).

The beds between this and the Burdiehouse Limestone are largely sandstones, which exhibit a variety of cross-bedding and other sedimentary structures. The limestone itself and the overlying Camps Shale are not well exposed but can be seen in small exposures on the shore. The limestone contains abundant ostracodes and also fish remains and plant fragments.

Above these is the 90 m-thick, massive and cross-bedded Dunnet Sandstone, which crops out from 60 m east of the Forth Bridge to nearly 530 m west of the Forth Bridge. At the western end of the sandstone outcrop, the overlying Dunnet Shale, the highest bed at the site, can be seen.

Interpretation

Miospore evidence shows that the sequence is of Asbian age and that the base of the section includes the junction between the *Perotrilites tessellatus–Schulzospora campyloptera* (TC) Zone and the overlying *Raistrickia nigra–Triquitrites marginatus* (NM) Zone (Neves *et al.*, 1973; and see Figure 2.2). The correlation of the Pumpherston Shell Bed with the Macgregor Marine Bands (Wilson, 1974, 1989) is consistent with a position close to this boundary, and records of B Zone goniatites from the Pumpherston Shell Bed in boreholes in West Lothian (Currie, 1954) support the Asbian age determination for these beds.

The shales, oil shales, and limestones of the West Lothian Oil-Shale Formation were deposited in large water bodies ('Lake Cadell') which were ponded up in the Midland Valley by a delta to the east (Greensmith, 1965; Loftus, 1984; Loftus and Greensmith, 1988; Whyte, 1994) (Figure 2.3). These lacustrine beds contain abundant faunas of thin-shelled ostracodes and fish remains, good examples of which can be seen within the Queensferry section. Although these water bodies were remarkably persistent, the situation was essentially dynamic and the characters of the lakes changed over time causing varying degrees of stratification of the water mass. Some of the carbonates, such as the Bogwood Limestone, were deposited in shallow conditions (Maddox and Andrews, 1987) while others, such as the

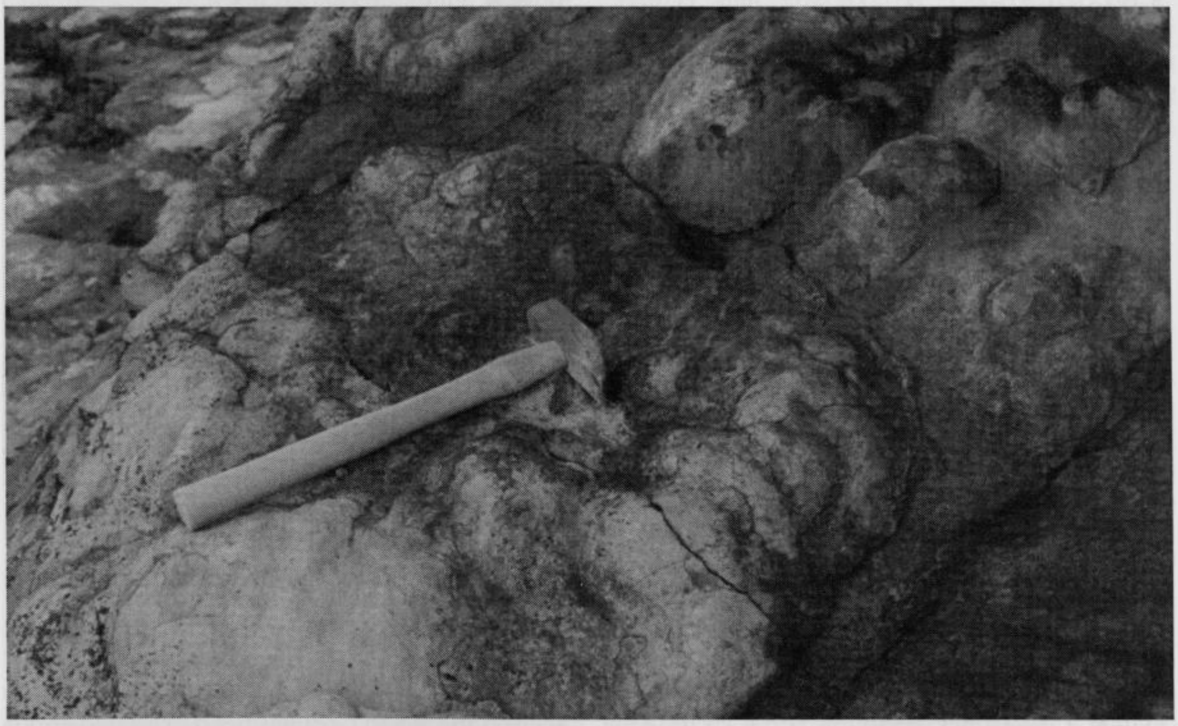


Figure 2.19 Stromatolitic algal domes in the Bogwood Limestone, West Lothian Oil-Shale Formation (Strathclyde Group, Asbian) at the Queensferry Shore GCR site. (Photo: M.A. Whyte.)

Burdiehouse Limestone, may have been deposited in more extensive stratified water bodies with water depths of 50–100 m (Loftus and Greensmith, 1988). Occasional marine influxes gave rise to shell beds with a restricted fauna, and delta progradations led to the occurrence of thick sandstone units such as the Dunnet Sandstone.

Conclusions

The Queensferry Shore is the best available section through the West Lothian Oil-Shale Formation and demonstrates the range of facies developed during its deposition. It has yielded stratigraphically important miospore assemblages and includes the Pumpherston Shell Bed, which is an important unit for correlation in the eastern parts of the Midland Valley. The section contrasts in character with coeval successions in Fife and is a vital link in understanding the depositional environments and palaeogeography of the time.

JOPPA SHORE, CITY OF EDINBURGH (NT 321 734)

Introduction

The Joppa Shore GCR site lies on the south shore of the Firth of Forth, 7 km east of the centre of Edinburgh (NT 321 734). The easterly dipping succession of the upper part of the Upper Limestone Formation (Arnsbergian) is the best remaining exposure of rocks of this age within the Midlothian Syncline. The sequence passes conformably upwards into younger strata of the Joppa Shore GCR site described by Cleal and Thomas (1996) in the *British Upper Carboniferous Stratigraphy* GCR volume and together these sites provide a composite exposure that is unique within the Midland Valley. The succession has been described by Peach *et al.* (1910) and Tulloch and Walton (1958), and in a guide by Tulloch (in Mitchell *et al.*, 1960).

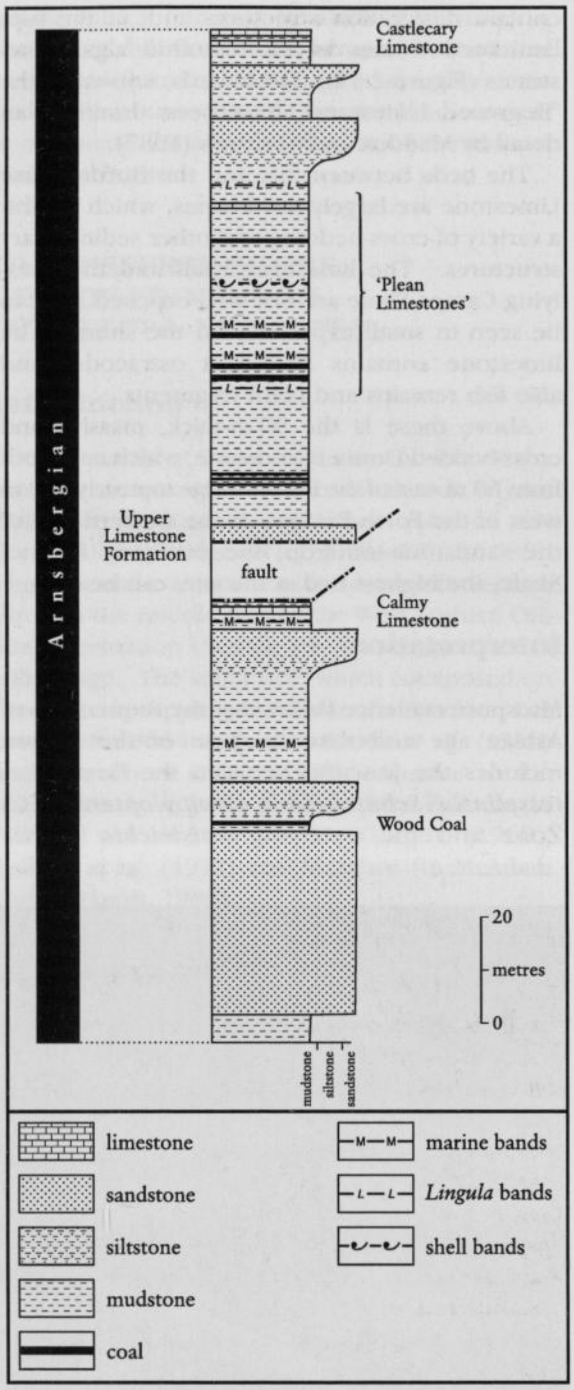


Figure 2.20 Simplified stratigraphical log of the Upper Limestone Formation (Clackmannan Group) succession at the Joppa Shore GCR site. Based on various sources and including information from Mitchell *et al.* (1960).

Description

The succession of the upper part of the Upper Limestone Formation at Joppa Shore is approximately 175 m thick although some strata have probably been faulted out (Figure 2.20). The basal bed is a massive sandstone which underlies the Wood Coal. Like most of the coals in this section the Wood Coal has been exploited and is no longer exposed. Above, there are sandstones and silty sandstones (12 m) capped by a pale seatearth (Tulloch and Walton, 1958). Overlying this are dark shales and bituminous shales (2 m) with ironstone nodules and fish remains, and these pass up into 3.5 m of shale with a low-diversity marine fauna including *Lingula* and the bivalves *Actinopteria* cf. *persculpta*, *Sanguinolites* cf. *clavatus*, and *Edmondia punctatella*. The last of these species is particularly common in a band 1 m above the base of the shale. The shale coarsens up through 8 m of siltstone and sandy siltstone into a sandstone with silty sandstone layers (7 m). Above this is a shale (1.5 m) with a restricted marine fauna of *Lingula* and several species of thin-shelled epifaunal and infaunal bivalves such as *Cardiomorpha*, *Prothyris* and *Sanguinolites*. The overlying Calmy Limestone (1.3 m), which is separated from this marine band by 1.5 m of siltstone and sandstone, is a crinoidal limestone with gigantoproductid and spiriferoid brachiopods.

There is a gap above the Calmy Limestone that may result from faulting (Tulloch in Mitchell *et al.*, 1960). Above this there are 25 m of sandstones, siltstones, fireclays and a few thin coals. The succeeding part of the succession (*c.* 40 m) is a variable succession of dark shales, siltstones, sandstones with fireclays and thin coals. A notable feature of this part of the succession is the presence of fossil bands containing *Lingula*, a band containing *Anthraconauta*, and a marine shale and limestone development with the most diverse marine fauna in the sequence; a fauna that includes *Fenestella*, *Antiquatonia* cf. *muricata* and *Pugilis* cf. *pugilis* (Tulloch and Walton, 1958; Wilson, 1967). A band containing *Lingula* also occurs about 3 m above the marine shale. The final 23 m of the succession is dominated by sandstones and seatearths. This is capped by the Castlecary Limestone (3.8 m), which is a shelly crinoidal limestone that marks the top of the Upper Limestone Formation and the boundary of the site.

Interpretation

The section is a typical section of the Upper Limestone Formation (E_2, Arnsbergian) and displays extremely well its component lithologies, including sandstones, siltstones, shales, seatearths and coals. Marine bands are less well developed than in the Lower Limestone Formation but the named horizons can be correlated over long distances. The occurrence of *Edmondia punctatella* in the lower part of the sequence below the Calmy Limestone is a distinctive feature, as is the higher horizon with thin-shelled bivalves (Wilson, 1967). The bands containing *Lingula* and other horizons in the centre of the succession are the equivalent of the Plean Limestones of the Central Coalfield (Tulloch in Mitchell *et al.*, 1960). The marine fauna that occurs towards the top of this part of the sequence is the most diverse marine fauna known from the Plean Limestones or their equivalents in the Midland Valley. The presence of the Castlecary Limestone is particularly interesting as this limestone is absent due to an unconformity throughout most of the Midlothian Syncline (Tulloch and Walton, 1958). Similar erosional loss of the limestone also occurs in other areas (Wilson, 1967). Thus the site is of vital importance in the detailed correlation of successions of this Namurian (E_2) age.

Conclusions

The Joppa Shore GCR site reveals the best section of the upper part of the Upper Limestone Formation (Arnsbergian) in the Midlothian Syncline. In addition to displaying the typical range of strata found in the Upper Limestone Formation it contains distinctive faunas that characterize particularly useful lithostratigraphical marker bands. It is an indispensable site in the network of Lower Carboniferous sequence correlations across the Midland Valley.

BILSTON BURN, MIDLOTHIAN (NT 270 648 and NT 282 648)

Introduction

Bilston Burn is a tributary of the River North Esk, lying 9 km south of Edinburgh. Its valley, which runs across the steeply dipping north-western limb of the Midlothian Syncline, exposes one of the finest sections of Carboniferous strata anywhere in Scotland; this ranging up from the upper part of the West Lothian Oil-Shale Formation (Strathclyde Group, Brigantian) through the Lower Limestone, Limestone Coal and Upper Limestone formations (Clackmannan Group, Brigantian to Arnsbergian) into the Upper Carboniferous Passage Formation. The Lower Carboniferous exposures (NT 270 648, NT 282 648) were, however, cut in two by culverting of the stream, which was carried out in order to reduce the underground flow of water into neighbouring collieries and which completely covered the exposures of the Limestone Coal Formation. Even in its restricted state, Bilston Burn still provides invaluable sections; now that mining has ceased consideration might be given to remedial conservation work at this site. The geology of Bilston Burn has been described by Peach *et al.* (1910), Macconachie (in Flett *et al.*, 1927) and Tulloch and Walton (1958). Macnair (1917), Macgregor *et al.* (1920), Robertson *et al.* (1949), Mitchell and Mykura (1962) and Wilson (1967) also give some details of the locality.

Description

An outcrop map illustrating the distribution of the principal formations and marine intervals at Bilston Burn is illustrated in Figure 2.21. The site includes about 100 m of strata belonging to the upper part of the West Lothian Oil-Shale Formation, the lower parts of which, including the Cephalopod Bed and two other marine horizons (Macconachie in Flett *et al.*, 1927), are no longer exposed. However, a fourth marine band, the Bone Bed Limestone, is exposed and lies 30 m below the top of the formation (Tulloch and Walton, 1958). Underneath the Bone Bed Limestone is a thin shale which has, at the base, a sandy layer with abundant and commonly fragmentary *Lingula* and fish remains. Marine fossils including bivalves (*Sanguinolites abdenensis*, *Actinopteria persulcata*) and the brachiopod *Schizophoria resupinata* (Macnair, 1917) occur in the shale and there is a band rich in *Rhipidomella* immediately below the limestone. The limestone is a bioclastic limestone (3 m) with crinoid ossicles and shell fragments. It is overlain by dark shales, grey sandy siltstone, micaceous sandstones and fireclays.

The basal bed of the Lower Limestone Formation, the Gilmerton Limestone, is obscured by old workings. Above the position of the limestone there are sandstones (some of which are ripple marked), subordinate mudrocks and a thin limestone, the Dryden Limestone (1.5 m), which rests on a bioturbated sandstone. The Dryden Limestone is sandy and contains crinoid remains and brachiopods. It is overlain by sandstone and fireclay, but above this the section becomes incomplete because of old workings for coal. Two seams, the North Greens Coal (1.4 m) and the Rough Parroty Coal (0.7 m), were formerly exposed here and both had shales above them containing *Lingula*.

The North Greens Limestone is the thickest limestone (27 m) in the Lower Limestone Formation at Bilston Burn, and because it has been extensively worked the lower part (3 m) is not exposed. The exposed beds are dark, fossiliferous, bedded limestones and calcareous shales. The top metre of the North Greens Limestone is ochreous and is overlain by a thick coarse-grained sandstone (20 m), the North Greens Sandstone, which is often red stained. Above the sandstone, the outcrops again become sporadic, but within the section there are sandstones, mudrocks and two limestones,

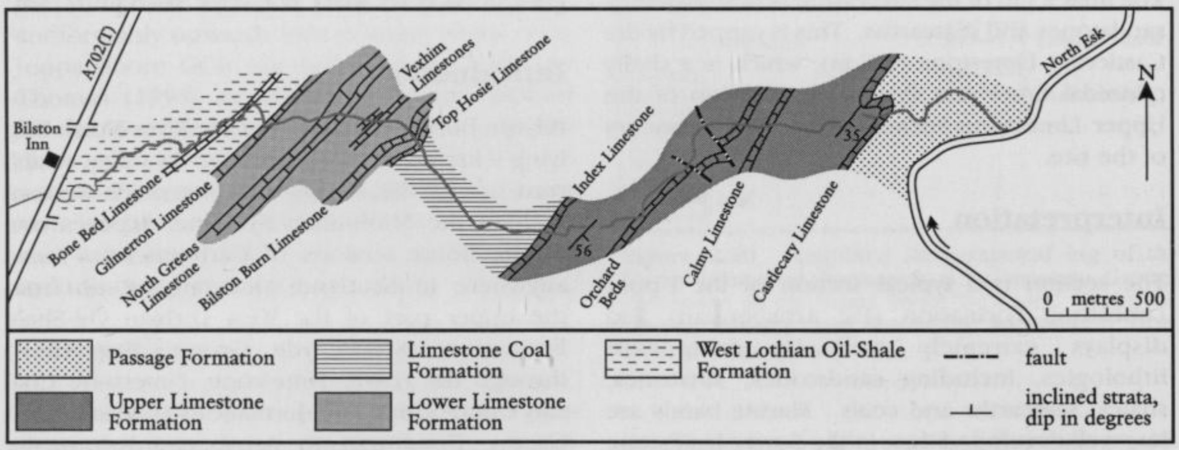


Figure 2.21 Simplified geological map of the Bilston Burn GCR site showing the outcrop distribution of the principal marine intervals and lithostratigraphical units in formations of the Clackmannan Group. After Macconachie in Flett *et al.* (1927).

the Lower Vexhim Limestone and Upper Vexhim Limestone. Coals that occurred immediately under the limestones (Lower Vexhim Coal or Niddrie Coal and Upper Vexhim Coal) have been extracted at the surface and are no longer exposed. Coals are also recorded lower down in the section, above the North Greens Sandstone (the Under Vexhim Coal), and stratigraphically higher, below the Bilston Burn Limestone.

The Bilston Burn Limestone is another thick and bedded limestone (15 m). The bottom part of this unit, which contained corals, is no longer visible. In places the limestone is rich in bryozoans (Macconachie in Flett *et al.*, 1927) and the uppermost bed, which is dolomitized, contains the curved spreite of *Zoophycos*. Shales above the Bilston Burn Limestone pass up into yellow sandstones (12.5 m), which near the top include a thin coal and which pass up into the Top Hosie Limestone. This is a sandy crinoidal limestone (0.75 m) capped by marine shales.

The cyclical succession of the Upper Limestone Formation contains a high proportion of sandstones and siltstones, but a number of marine intervals and some coals are also present. The basal bed is the brown-weathering and dolomitic Index Limestone (1.2 m), which contains the gigantoproductid brachiopod *Latiproductus* cf. *latissimus*. The shales (3.4 m) above the limestone have provided a marine fauna (Peach *et al.*, 1910) and pass up through siltstones and sandstones (1.6 m) into a thick sandstone (5.8 m), the Joppa Sandstone. Above this sandstone there are 17 m of siltstones and sandstones capped by fireclays and coals. Marine fossils including abundant orthotetoid brachiopods have been found in sandstone bands 2–3 m above the Joppa Sandstone (Tulloch and Walton, 1958). Marine fossils also occur in a thin sandstone 1.4 m higher in the succession. One of the coals, named the 'South Parroty Coal', has been worked at outcrop and is no longer exposed. An incomplete section of sandstones and siltstones (50 m) lies between the coal and the Lyoncross Limestone.

The Lyoncross Limestone in Bilston Burn is developed as a siltstone with ironstone nodules (0.75 m) and marine fossils overlying a siltstone (0.45 m) containing large carbonate concretions with a cone-in-cone structure. A thin coal lies 0.4 m lower in the section. Productoids, *Lingula*, palaeotaxodont bivalves and bellerophontids have been recorded from the Bilston Burn outcrop (Tulloch and Walton, 1958). About 40 m of strata lie between the Lyoncross Limestone and the Orchard Beds and these are noteworthy for the presence of three or four bands containing *Lingula*. The lowest of these lies only 2 m above the Lyoncross Limestone and contains fish remains as well as the characteristic inarticulate brachiopod. A thick sandstone and other strata separate this band from a thin coal and shales in which plants and possible *Lingula* fragments have been recorded (Tulloch and Walton, 1958); 2.3 m higher in the sequence is a thicker shale (1.6 m) with *Lingula* and fish remains. The highest band containing *Lingula* (0.4 m), which also contains small bivalves, lies 8 m above this.

The Orchard Beds (23 m) comprise a shale-dominated succession with interbedded siltstones, sandstones, impure limestones, ironstone (siderite) nodules and a rich marine fauna. The marine fauna is particularly abundant and diverse at the base and top of the section. The lower fauna includes productoids (*Eomarginifera*, *Dictyoclostus* cf. *muricatus*, *Latiproductus* cf. *latissimus*) and other brachiopods (*Pleuropugnoides*, *Schizophoria*, *Composita*, spiriferoids, orthotetoids, *Lingula*), epifaunal bivalves (*Aviculopecten*, *Pernopecten*) and infaunal bivalves (*Cypricardella*, *Phestia*, *Nuculopsis*, *Sanguinolites*, *Parallelodon*, *Schizodus*), gastropods (*Euphemites*, *Bucaniopsis*, *Glabrocingulum*), fenestellid bryozoans and crinoid remains (Tulloch and Walton, 1958). The upper fauna contains productoids (including *Latiproductus* cf. *latissimus*), spiriferoids, bivalves, gastropods, trilobites and crinoid remains.

The sequence (46 m) between the Orchard Beds and the Calmy Limestone contains a number of thin coal seams including the Wood Coal. Above the latter there are fireclays, siltstones and shales (6.3 m), and above this is a thick shale (14.7 m) capped by silty sandstone (2.2 m) on which the Calmy Limestone rests. Within the shale there are a number of levels at which *Lingula* or marine fossils are found, and close to the base, one of these bands contains abundant *Edmondia punctatella* together with *Actinopteria* and *Sanguinolites* cf. *clavatus*. *Sanguinolites* also occurs in a higher band with marine fossils. The Calmy Limestone (1.8 m) consists of three beds of limestone separated by thin shales. The limestone contains crinoids and is overlain by shales (5.2 m), which contain abundant orthotetoid brachiopods as well as *Schizophoria*, chonetoids, spiriferoids and the bivalve *Polidevcia*.

The strata (124 m) between the Calmy Limestone and Castlecary Limestone are principally noteworthy for the occurrence of a group of thin marine bands, which are the local representatives of the Plean Limestones. The lowest of these, lying 64 m above the Calmy Limestone, rests on a coal (0.3 m) and contains *Lingula*, *Orbiculoidea* and *Sanguinolites*. Another thin shale (15 cm), which lies 4 m higher, contains the bivalves *Promytilus*, *Sanguinolites* and *Sedgwickia*, and 3.6 m above that there is a thin (8 cm) shale with bivalves, conchostracans (*Euestheria*) and fish remains. The highest of these marine bands is 21 m higher in the sequence and 30 m below the Castlecary Limestone. It contains a more diverse fauna than the other horizons, including fenestellid bryozoans, the productoids, *Dictyoclostus* aff. *muricatus* and *D. pugilis*, orthotetoids, bivalves and gastropods. The Castlecary Limestone, which marks the top of the Upper Limestone Formation, is made up of two beds (1.1 m and 1.4 m) of fine-grained, brown-weathering limestone with a shale parting. It is overlain immediately by sandstone of the Passage Formation.

Interpretation

The upper West Lothian Oil-Shale Formation and the Lower Limestone Formation in Bilston Burn show the Yoredale-type cycles, which typify this part of the Scottish Lower Carboniferous succession. In these, the limestones and marine shales were deposited in open shallow-shelf conditions (Wilson, 1974, 1989) and the cycle passes up through delta-front shales, siltstones and sandstones into the sandstones, fireclays and coals of the delta top. However, as in other parts of the Midland Valley, the succession in the Midlothian Basin shows considerable thickness and facies variations (Tulloch and Walton, 1958). Thus, the relatively thick sequence at Bilston Burn provides an important reference section for the basin and for correlations between this area and other parts of the Midland Valley.

The beds immediately below the Gilmerton Limestone are one case where the sections on either side of the Midlothian Basin show marked differences and have presented correlation problems (Macnair, 1917; Tulloch and Walton, 1958). Tulloch and Walton (1958) have suggested that the Bone Bed Limestone correlates with the Lower Crichton Limestone of East Lothian and that the latter correlates with the Catcraig Middle Limestone of Dunbar. Westwards the Bone Bed Limestone correlates with the Under Limestone of West Lothian (Tulloch and Walton, 1958) and through this with the Blackbyre Limestone of the Paisley district (Wilson, 1989). Thus the Bilston succession forms an important link between the eastern and the western ends of the Midland Valley (Figure 2.4).

This is also true at higher horizons, where the Gilmerton Limestone is the correlative of the Hurlet Limestone of Paisley and the Catcraig Upper Limestone of Dunbar, and the Dryden Limestone correlates with the Craigenhill Limestone of the west and the Skateraw Lower Limestone of the east. By the same token, the North Greens Limestone correlates with the Blackhall Limestone of the Central Coalfield and the Skateraw Middle Limestone of Dunbar (Figure 2.4).

In the strata between the Dryden Limestone and the North Greens Limestone the development of coals is interesting, and the Rough Parroty Coal lies at the level of the well-known Gilmerton Ironstone, which is found to the north of Bilston (Peach *et al.*, 1910; Macgregor *et al.*, 1920; Tulloch and Walton, 1958). The North Greens Sandstone, which occurs above the North Greens Limestone, is best developed in the northern parts of the Midlothian Basin and has been compared with the Seafield Tower Sandstone of West Fife (Macconachie in Flett *et al.*, 1927).

The four limestones in the upper part of the Lower Limestone Formation correlate with the four limestones of the Hosie Limestones of the Central Coalfield (Macgregor, 1930; Wilson, 1989) although the Midlothian succession is lithologically more varied than that of the Central Coalfield. This correlation is supported by the similarity between the coal under the Bilston Burn Limestone and the Lillie's Shale Coal of Paisley (Tulloch and Walton, 1958).

The Upper Limestone Formation also exhibits a Yoredale cyclicity, but the marine horizons tend to be more uniform and older local names for the major marine horizons have been replaced by the standard nomenclature developed in the Central Coalfield. However, the detailed correlation of some of the other horizons is less certain and the Bilston Burn succession provides valuable information about these and about the stratigraphy and palaeoenvironments of the formation as a whole.

The Index Limestone of Bilston Burn is not as fossiliferous as its counterpart in the Central Coalfield but does contain *Latiproductus* cf. *latissimus* which is widespread at this horizon (Wilson, 1967). The reduced marine influence in this and other marine horizons in the formation, when compared with equivalent strata in the Central Coalfield Basin, may reflect a closer proximity to the delta of the river system, which was flowing in from the north-east end of the Midland Valley (Figure 2.3). The Joppa Sandstone and some of the other thick sandstones within the succession may represent major distributary channel sandstones deposited during phases of delta advance. The Joppa Sandstone lies at about the same level as the Bishopbriggs Sandstone of the Glasgow district, and the unnamed marine horizons above it correspond broadly with the Huntershill Cementstone of the Central Coalfield (Tulloch and Walton, 1958). The overlying group of coals and fireclays, including the South Parroty Coal, represent delta-top environments.

The occurrence of the Lyoncross Limestone at Bilston Burn is the only surface outcrop of this horizon within the Midlothian Basin. Like the Index Limestone, it is less fossiliferous than the same horizon in more westerly areas (Wilson, 1967). The bands containing *Lingula* between the Lyoncross Limestone and the Orchard Beds lie at a similar level to thin *Lingula* or marine beds in the Stirling–Clackmannan and Central Coalfield areas (Macgregor *et al*., 1925; Francis *et al*., 1970). They represent restricted marine and estuarine or brackish-water environments. In contrast, the Orchard Beds contain the most diverse fauna in the Bilston Burn Upper Limestone Formation succession and this is true of its development throughout the Midland Valley (Wilson, 1967). The presence of *Latiproductus* cf. *latissimus* in the Bilston Burn fauna is of interest. This species has a restricted distribution at this horizon and is commonly found only in more southerly and easterly parts of the Midland Valley (Wilson, 1967). The upper parts of the Orchard Beds are also the only horizon in the Bilston Burn succession at which trilobite remains, mucronate pygidia of *Paladin*, are common.

The Calmy Limestone is poorly fossiliferous as compared to much richer developments in the Central Coalfield Basin (Wilson, 1967) and the most interesting feature of this marine horizon is the fauna of the underlying shales. These contain a band rich in *Edmondia punctatella*, which is also characteristically found in a thin band immediately below the Calmy Limestone at other localities throughout the Midland Valley. In the Central Coalfield this interval is usually a highly carbonaceous shale but in the Bilston Burn it is a lighter-coloured silty mudstone (Tulloch and Walton, 1958). The marine bands, which are found between the Calmy Limestone and Castlecary Limestone, equate broadly with the Plean Limestones of the Stirling–Clackmannan Basin. However, the detailed correlation of individual horizons is uncertain. At Bilston Burn it is the highest of these bands that contains the richest marine fauna, while in the type area it is the lowest of the three limestones of the Plean Limestones that has the most diverse fauna (Wilson, 1967). The Castlecary Limestone has not yielded a distinctive fauna but is commonly overlain by a shale with *Curvirimula* and fish remains (Wilson, 1967). This shale is present at **Joppa Shore** to the north (see GCR site report, this chapter) but at Bilston Burn an erosively based sandstone rests directly on the limestone. In the southern and western parts of the Midlothian Basin the Castlecary Limestone is apparently entirely absent due to an unconformity (Tulloch and Walton, 1958). Similar erosive loss of the Castlecary Limestone occurs elsewhere in the Midland Valley (Macgregor, 1930; Francis in Craig, 1991).

Conclusions

Bilston Burn is a major, inland Lower Carboniferous section proving much of the local Carboniferous succession and providing an invaluable standard for the upper West Lothian Oil-Shale Formation and the Lower Limestone Formation and Upper Limestone Formation of the Midlothian Basin. This is an irreplaceable section for the Lower Carboniferous rocks in the Lothians and is of vital importance for comparisons between sites in the Midland Valley. The sedimentary facies and faunal associations are of great significance to the understanding of palaeoenvironmental and palaeogeographical change during the Brigantian–Arnsbergian time interval.

SKOLIE BURN, WEST LOTHIAN (NS 984 619–NS 987 624)

Introduction

The Skolie Burn is a tributary of the Briech Water and, 0.9 km west of Addiewell Station, a stream section (NS 987 624–NS 984 619) in it provides the best section of the upper part of the Lower Limestone Formation and the basal beds of the Limestone Coal Formation (late Brigantian and early Pendleian) on the eastern side of the Central Coalfield. The section has been described by Macnair (1917) and Macgregor and Anderson (1923). Further information relating to the site is given by Cameron *et al.* (1998).

Description

The section overlies an intrusive picrite sill and the basal beds of the sequence are baked at the sill contact. The sequence, which is 20 m thick, is largely argillaceous and includes at least three of the four marine horizons collectively known as the 'Hosie Limestones' (Figure 2.22). The lowest marine band is a sandy limestone (1.2 m) resting on baked sandstone (2.0 m). Above this, 2 m of dark shale are overlain by a second prominent marine horizon, an argillaceous limestone bed (1 m) that passes up into a sequence of shale with thin argillaceous limestone interbeds (2.6 m) which are also of marine aspect. *Lingula* has been recorded from the shales immediately above the basal sandy limestone bed (Macgregor and Anderson, 1923) and a diverse brachiopod-dominated marine fauna including productoids (*Eomarginifera*), rhynchonellids and spiriferoids has been recorded from the lower two limestones (Cameron *et al.*, 1998). In addition, trepostomous bryozoans and the bivalve *Posidonia membranacea* are present (Cameron *et al.*, 1998). These marine beds pass up into a dark fireclay that becomes sandy towards its top (1.8 m), and this is overlain by a coal (0.4 m). Above this are further argillaceous fireclays with stigmarian roots (2.3 m) capped by a thin, nodular, calcareous band with rootlets (0.15 m). This is sharply overlain and separated from another marine horizon by 1.5 m of dark shale. This marine unit, a thin crinoidal limestone (0.6 m), is separated from the argillaceous limestone (1.8 m) of a further marine horizon by fossiliferous shales (1 m). Above this limestone, 4 m of dark shales

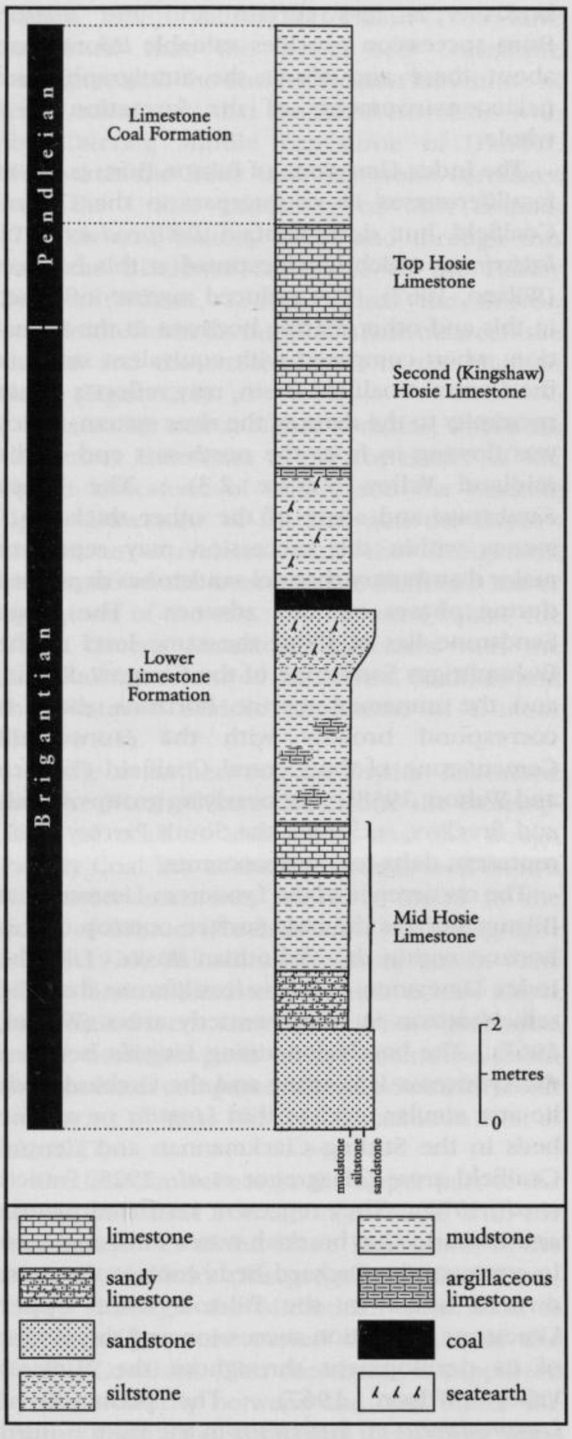


Figure 2.22 Simplified stratigraphical log of the Lower Limestone Formation and Limestone Coal Formation (Clackmannan Group) at the Skolie Burn GCR site.

with siderite nodules are recorded and a marine fauna at their base includes abundant specimens of *Posidonia corrugata*.

Interpretation

The predominantly argillaceous sequence shows marine limestones and shales separated by a unit of coal and fireclays, and the presence of *Posidonia membranacea* and the abundance of *Posidonia corrugata* confirms that these are at the horizon of the Hosie Limestones (Wilson, 1989). These limestones have not been given local names in the Skolie Burn area, and Macgregor and Anderson (1923) named them by correlation with the Carluke area, 18 km to the south-west, from which area the collective term 'Hosie' is probably also derived. The Hosie Limestones sequence varies considerably across the Midland Valley (Wilson, 1989) but typically contains four marine horizons. In the Paisley area these are known in ascending order as the Main Hosie Limestone, Mid Hosie Limestone, Second Hosie Limestone and Top Hosie Limestone (Hinxman *et al.*, 1920; Whyte, 1981; Wilson, 1989; and see Figure 2.4) and the equivalents in the Carluke region are the Birkfield Limestone, First Kingshaw Limestone, Second Kingshaw Limestone and Lingula (or Top Hosie) Limestone respectively (Hinxman *et al.*, 1921; Whyte, 1981). Macgregor and Anderson (1923) considered that the two limestone bands below the coal and fireclay at Skolie Burn were the equivalents of the Birkfield (Main Hosie) Limestone and First Kingshaw (Mid Hosie) Limestone, but more recently Cameron *et al.* (1998) have re-correlated both of these limestones and the intervening marine beds with the Mid Hosie Limestone. The two marine limestones above the coal and fireclay are correlated with the Second Kingshaw (Second Hosie) Limestone and the Top Hosie Limestone (Macgregor and Anderson, 1923; Cameron *et al.*, 1998). At several localities in the Central Coalfield these two horizons may be difficult to separate and form a compound marine band. The coal and fireclay horizon in the centre of the Skolie Burn section is the local equivalent of the Lillie's Shale Coal and Hosie Fireclay horizon of the Paisley district (Hinxman *et al.*, 1920; Magregor *et al.*, 1925). This is a widespread though highly variable horizon, which may mark a disconformity in the sequence (Whyte, 1981). The top of the Top Hosie Limestone is the marker for the top of the Lower Limestone Formation (Browne *et al.*, 1999) and in the Skolie Burn section the uppermost shales thus belong to the base of the Limestone Coal Formation.

The correlation of the Hosie Limestones in Fife and Midlothian and in the Bathgate Hills, where they are interbedded with volcanic rocks (Cameron *et al.*, 1998), has presented many difficulties (Wilson, 1989) due to their different and highly variable development in these areas. The Skolie Burn sequence is the only good section at this level on the eastern margin of the Central Coalfield and this fossiliferous sequence thus forms a vital link in correlating this group of strata between eastern and western Scotland.

Conclusions

The Skolie Burn GCR site shows an excellent late Brigantian to early Pendleian section through the Hosie Limestones and associated, largely argillaceous, strata at the top of the Lower Limestone Formation and base of the Limestone Coal Formation. With its central position within the Midland Valley, the section and its fossils are of vital stratigraphical importance in correlating these late Dinantian and early Silesian rocks across the Midland Valley of Scotland.

PETERSHILL, WEST LOTHIAN (NS 985 695 and NS 987 707)

Introduction

High in the hills 1 km to the north-east of Bathgate a staggered line of old quarries highlight the outcrop of a thick sedimentary intercalation within the Bathgate Hills Volcanic Formation (Bathgate Group). The largely volcanic sequence of the Bathgate Hills Volcanic Formation makes up the elevated topography of the Bathgate Hills and dips westwards beneath younger rocks of the Central Coalfield Basin on whose eastern margin it lies. The Petershill GCR site embraces two of these quarries, the Petershill Reservoir Quarry (NS 985 695) and the Rifle Range Quarries (NS 987 707), within which there are exposures of the Petershill Limestone (upper Brigantian) and some associated clastics. The limestone, which has long been famous for its sedimentary and palaeontological features, has been painstakingly described by Jameson (1980), who has also provided a thorough review of previous work. Bassett (1958) and Stephenson and Monro (in McAdam and Clarkson, 1986) have written excursion guides to the locality. Other publications with relevant information are Peach *et al.* (1910), Macgregor and Anderson (1923), Hill (1938–1941), Robertson *et al.* (1949), Parks (1954), Muir and Hardie (1956), Mitchell and Mykura (1962), Jameson (1987) and Cameron *et al.* (1998).

Description

A schematic cross-section showing the facies relations in the Petershill Limestone at this site is illustrated in Figure 2.23. On the east bank and margin of Petershill Reservoir Quarry (the reservoir is now drained) the Petershill Limestone comprises bedded limestones and slightly argillaceous limestones (4 m) containing *Thalassinoides* burrows, patches of *Siphonodendron junceum*, abundant solitary corals, spiny productoids and echinoids. The solitary rugose corals occur in aggregations of several species, including *Aulophyllum pachyendothecum* and *Koninckophyllum*, mostly in life position. Endothyrid foraminifera, ostracodes and filamentous and dasycladacean algae have also been recorded from these beds (Jameson, 1987). At the northern end of the quarry, a small fault downthrowing to the south reveals a small section of the underlying bioturbated argillaceous limestones and shales that contain gigantoproductids, *Eomarginifera*, *Hyalostelia* sponge spicules and the phosphatic tubes of *Sphenothallus*.

Exposed at the southern end of the quarry are more massive limestones (9 m), the principal facies of a 'biohermal buildup' first recognized by Jameson (1987). These overlie the bedded limestones and are separated from them by an erosion surface (see Figure 2.23). At the base, cream-coloured lime mudstones and wackestones contain a relatively low-diversity assemblage of small productoids and sponges (*Hyalostelia*) and show stromatactoid cavities and brecciation. Fenestellid bryozoans are also present. This passes up into a high-diversity productoid–sponge–rostroconch assemblage. In places, either *Hyalostelia* sponge spicules or fenestellid bryozoan fronds have formed mats protecting and stabilizing the sediment surface. Small shelter cavities occur under some of the bryozoan fronds. Myodocopid ostracodes (*Entomoconchus*) are common in this facies, and productoids (namely *Echinoconchus elegans* and *Antiquatonia hindi*), spiriferoids, orthotetoids, fistuliporoid bryozoans, *Hexaphyllia*, *Amplexus coralloides*, ostracodes, encrusting foraminifera, worm tubes, *Pinna* and *Conocardium* are also present. Above this, there are beds of poorly sorted crinoidal packstone. Massive beds seen on the west side of the quarry are separated from the overlying moderately well-sorted crinoidal packstones (1.2 m) by an erosion surface. These are overlain in turn by dark, sandy micaceous siltstones.

The Rifle Range Quarries run for about a kilometre along the strike of the beds, and in these the lower parts of the Petershill Limestone consist of heterogeneous packstones (Figure 2.23), which show marked variations in grain size, sorting and composition. The lowest 3–4 m of this facies comprise cross-bedded crinoidal packstones with bands containing

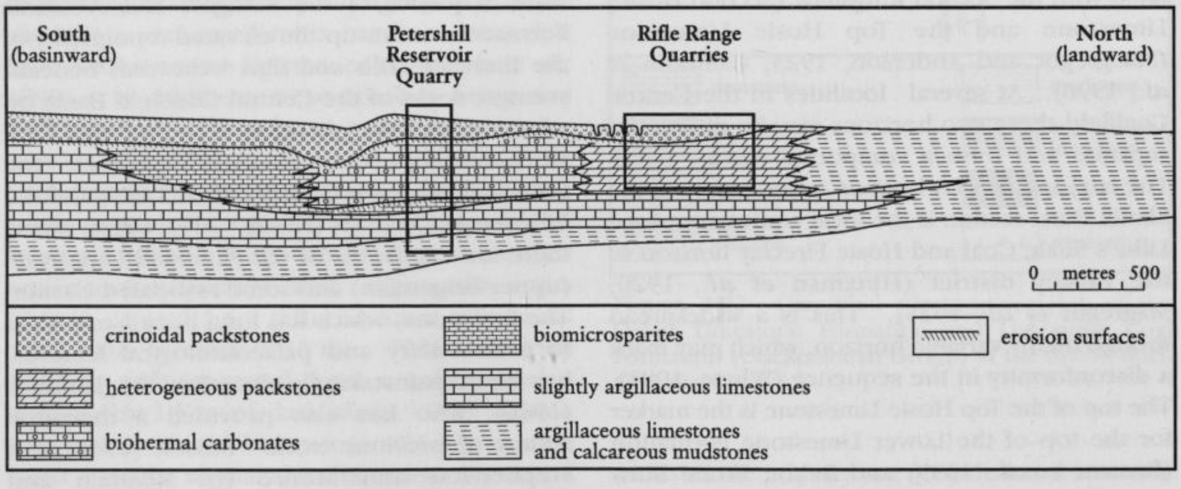


Figure 2.23 Schematic north–south cross-section showing facies distributions in the Petershill Limestone (upper Brigantian) at the Petershill GCR site, Bathgate. After Jameson (1987).

large corals (*Actinocyathus floriformis*, *Lithostrotion vorticale*, *Palastraea regia*, *Thysanophyllum*, *Syringopora*, *Siphonodendron*) and the demosponge *Chaetetes*. Although much of the fauna is *in situ*, some of the coral colonies appear to have been overturned and have sometimes re-grown. Bands, typically 15–20 cm thick and crowded with gigantoproductids, also occur and show disarticulated and stacked valves. In addition to small-scale planar and trough cross-bedding, some beds show lenticular bedding. In the centre of the sequence a slightly more argillaceous, less well-sorted and finer-grained unit with *Zoophycos* and solitary corals dies out southwards along the quarry face. In general, beds also get finer to the south. A thin clay way-board occurs within the upper part of these beds and at its top an erosion surface cuts 3 m down into the underlying limestone. Above this there are impersistent sandstones and tuffs and laterally extensive crinoidal packstones and grainstones, which also have an eroded upper surface. This erosion surface is covered by a thin veneer of sandstone and by black shales, though at the northern end of the quarries a basalt lava rests directly on the limestones. Both of these erosion surfaces have associated fissure systems, which contain an infill of tuff, plant-bearing sandstone and limestone intraclasts.

Interpretation

The Petershill Limestone is part of a major sedimentary intercalation within the volcanic sequence of the Bathgate Hills Volcanic Formation. The location of this volcanic activity may be linked to the major structural feature of the Burntisland High (Jameson, 1987; and see Figure 2.3c). The Petershill Limestone is correlated with the Main Hosie Limestone and Mid Hosie Limestone of the Central Coalfield Basin (Cameron *et al.*, 1998; see also Macnair, 1917). On the eastern margin of the Central Coalfield Basin and to the south of Bathgate, where the volcanics are not present, these two limestones are relatively thin, with a combined thickness of less than 4 m (Macgregor and Anderson, 1923; Cameron *et al.*, 1998). However, close to Bathgate, where the volcanics are present, the limestone thickens rapidly and then more gradually thins northwards. This unusual and thicker development of the Petershill Limestone accumulated in the shallower water around a submarine high formed by the volcanics.

The Petershill Limestone formed during a relatively quiescent phase in the volcanic activity. The lavas, which underlie this marine limestone, are overlain by a sequence of tuffs and sandstones with plant remains. These indicate a prolonged period of subaerial weathering prior to the marine transgression. Marine deposition commenced with the formation of a thin dark shale that passed up into the calcareous mudstones and argillaceous limestones of the basal parts of the Petershill Limestone. These appear to have formed in a shallow lagoonal environment (Jameson, 1987). As the transgression continued, purer limestones were deposited in the southern part of the outcrop (Jameson, 1987). Representatives of both the argillaceous limestones and the purer limestones are seen on the eastern bank of the Petershill Reservoir Quarry.

Following a subsequent regressive episode, during which the erosion surface at Rifle Range Quarries was formed, a more varied suite of carbonates were deposited. In particular, the heterogeneous packstones of the Rifle Range Quarries were deposited in a shallow-water nearshore area, which was subject to relatively high-energy conditions. The turbulence caused movement of crinoid debris, overturning of corals and the disarticulation and stacking of gigantoproductid valves. These carbonate shoals protected a landward lagoon in which argillaceous limestones and calcareous mudstones, similar to those at the base of the Petershill Limestone, continued to form (Jameson, 1987). At the same time, but on the seaward side of the shoals and in slightly deeper water, the growth of sponges, bryozoans and algae contributed to the development of the massive limestones that formed the core of the biohermal buildup at Petershill Reservoir Quarry (Jameson, 1987). Jameson (1987) has found evidence from geopetal structures to indicate that the buildup had a relief of 1.5–2 m above the local sea floor and that the flanks sloped at about 10° to 12°. The sequence of assemblages within the bioherm indicates an initial pioneer community colonizing an area of algally stabilized sediment and building up a low mound. The increased abundance and diversity of the fauna led to rapid in-situ accumulation and stabilization of the mound. Continued upward growth, however, exposed the mound to increased current activity and led to the formation of the crinoidal beds, which cover the mound. These show that the mound was not able to withstand significant current activity.

The erosion surfaces at the top of the Petershill Limestone indicate regressive phases of erosion and subaerial exposure separated by a minor transgression during which crinoidal grainstones formed (Jameson, 1987). The fissures preserve in their infill sedimentary material, which is not preserved elsewhere, and which indicates the prolonged nature of these two events. The presence of tuffaceous material in the fissures indicates some volcanic activity. Intermittent volcanic activity also took place during the deposition of the limestone since the impersistent clay wayboards are bentonite horizons resulting from the alteration of ash-fall deposits (Stephenson and Monro in McAdam and Clarkson, 1986; Jameson, 1987).

The faunas of the Petershill Limestone are not only of great palaeoecological importance but are also of immense taxonomic significance. This is the source horizon for the type material of a number of important and well-known corals including *Actinocyathus floriformis*, *Aulophyllum pachyendothecum*, *Koninckophyllum echinatum* and *Caninia juddi* (Hill, 1938–1941), and Parks (1954) based his study of morphological variation in *Aulophyllum pachyendothecum* on material from Petershill Reservoir Quarry. Hinde (1887–1912) used material from Petershill in his description of the sponge *Hyalostelia*, and Davidson (1851–1886, 1860) also used material from this area in brachiopod descriptions. Clark (1960) described conodonts from the Petershill Limestone, and Latham (1932) lists ostracode species from quarries in the limestone. Fleming's (1825) description of *Dentalium indistincta* (= *Sphenothallus indistincta*) is most probably based on Petershill material (the first scientific description of a sphenothallid tube) and, in addition, spirorbid worm tubes have been recorded from the Petershill Limestone by Etheridge (1880). The foraminiferal assemblage indicates a late Viséan age for this unit (Jameson, 1980).

Conclusions

The Petershill GCR site is a classic and important site famous for its Lower Carboniferous fossils and its carbonates. The Petershill Limestone (upper Brigantian) lies within the predominantly volcanic sequence of the Bathgate Hills Volcanic Formation and shows clearly the effect of volcanism on local sedimentation. The lateral and vertical facies variations within the Petershill Limestone are of immense interest to carbonate sedimentologists and palaeontologists. The limestone comprises a unique biohermal buildup with a diverse, abundant and well-preserved fauna, and a laterally equivalent facies of coarsely bedded limestones with corals and gigantoproductids that were deposited on an adjacent shoal area. The faunas of the Petershill Limestone remain of great palaeoecological, stratigraphical and taxonomic significance.

GARGUNNOCK BURN, STIRLING (NS 709 930–NS 707 933)

Introduction

Situated 9 km west of Stirling, the Gargunnock Burn (NS 707 930–NS 707 933) runs down the north-facing scarp of the Gargunnock Hills, which are the north-western extension of the Campsie Fells. A particularly fine stream section here reveals excellent outcrops of the Inverclyde Group (Tournaisian) lying between Upper Old Red Sandstone (Stratheden Group) below and the Clyde Plateau Volcanic Formation (Strathclyde Group) above. The section is critical in monitoring the subtle environment changes associated with earliest marine influences of early Tournaisian (Lower Carboniferous) age in the Gargunnock area. Read (in Francis *et al.*, 1970) has provided a meticulous account of the section, and detailed sedimentological descriptions and interpretations have been supplied by Belt *et al.* (1967) and Read and Johnson (1967).

Description

Within the Inverclyde Group at the Gargunnock Burn GCR site three formations are recognized. These are, in upward sequence, the Kinnesswood Formation, the Ballagan Formation and the Clyde Sandstone Formation. Representative sections of the Kinnesswood Formation and Ballagan Formation at this site are illustrated in Figure 2.24. The Kinnesswood Formation, formerly referred to as the 'Cornstone Beds' (Francis *et al.*, 1970), is truncated at its base by a minor fault, but the loss of section is probably small and the formation here is 100 m thick (Francis *et al.*, 1970). The unit is largely composed of sandstones with subordinate siltstones

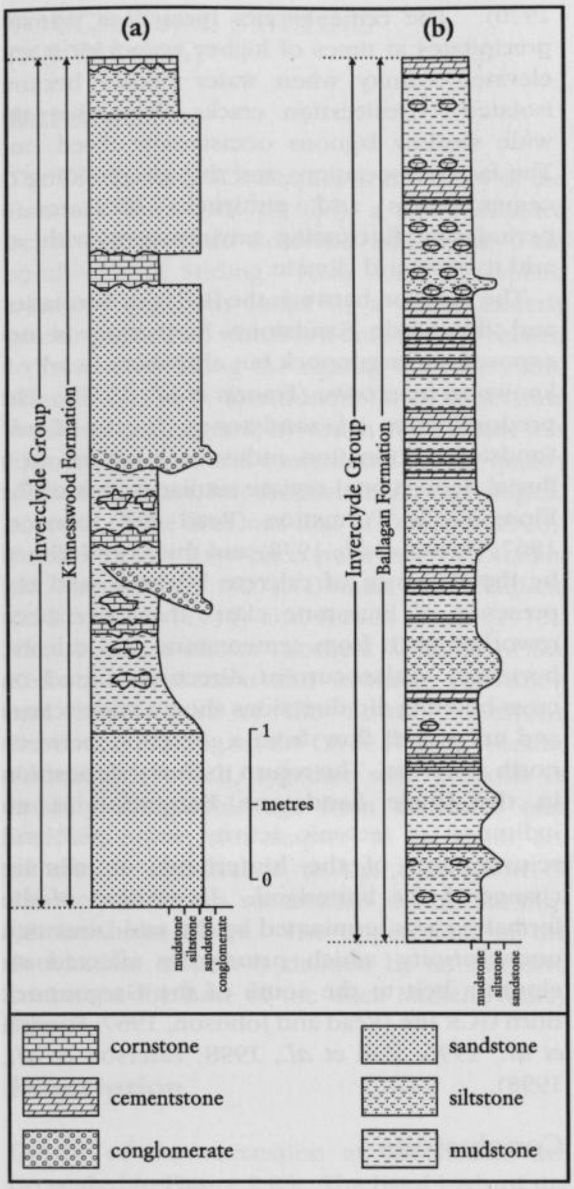


Figure 2.24 Representative sections of (a) the Kinnesswood Formation and (b) the Ballagan Formation of the Inverclyde Group at the Gargunnock Burn GCR site. Based on information in Belt *et al.* (1967) and Francis *et al.* (1970).

and mudrocks. These are arranged in small-scale fining-upward cycles of sandstone passing up into, or overlain by, finer-grained rocks (Read and Johnson, 1967; Francis *et al.*, 1970). The sandstones are usually 3–7 m thick and vary from white to red or reddish-purple in colour. They typically show planar or trough cross-bedding and cut down into and rest disconformably on the rocks of the previous cycle. The basal parts of sandstone beds are often conglomeratic and contain calcrete clasts, breccias and scattered pebbles of quartz or quartzite. The siltstones and mudrocks are normally red in colour but may show mottling with green and buff colorations. These parts of the cycles are usually less than 2 m thick but have been truncated and in some cases entirely cut out by erosion at the base of the next cycle. The most distinctive feature of the Kinnesswood Formation is the presence of irregular layers and nodules of calcrete (see Figure 2.24). These are concretionary carbonates, which at Gargunnock are dolomitic, and occur in the upper part of cycles both in the mudrocks and in the sandstones. In some instances corroded grains of quartz can be seen floating in the carbonate. The reworking of brecciated calcrete fragments at the base of cycles shows their penecontemporaneous origin.

The junction between the Kinnesswood Formation and the Ballagan Formation is not exposed in the Gargunnock Burn but lies within a 3 m gap in the exposures. A total of 50 m of Ballagan Formation are present in the section but the upper beds of the formation have been cut out by a strike fault which has resulted in the lower beds being faulted against sandstones of the overlying Clyde Sandstone Formation.

The Ballagan Formation is finer in character than the Kinnesswood Formation and is composed of cementstone bands and nodules, interbedded with mudrocks and sporadic fine sandstones (see Figure 2.24). The mudrocks, which are the dominant lithology, occur in beds up to 2 m thick and usually vary in colour from green to grey although some are red or brown in colour. They may be fissile or massive and are often silty or sandy in character. Occasionally they may pass into, or be interlaminated with, fine sandstones in beds up to 1 m thick. Although some of the cementstone nodules may be of secondary (diagenetic) origin, most of the nodules and the cementstone layers are primary dolomicrites. The cementstone layers are usually thin and the maximum thickness at Gargunnock is about 0.4 m. Boundaries with the adjacent mudrocks may be sharp or gradational and some bands show traces of internal lamination or brecciation. One stratified cementstone in the middle of the section has shrinkage cracks on its upper surface. Fish remains and obscure thin-shelled spheroidal and vermiform bodies have also been recorded from this bed (Francis *et al.*, 1970).

The Clyde Sandstone Formation, formerly known locally as the 'Downie's Loup Sandstones' (Francis *et al.*, 1970), is seen in outcrops south of, and upstream from, the fault that truncates the Ballagan Formation. The sequence is about 70 m thick, but only about 20 m are exposed. Exposures are most complete towards the base of the sequence and are poor above the Downie's Loup waterfall, which is formed by a 7 m-thick intrusive sill. The sequence is dominated by white or greenish sandstones, which vary in grain size from fine-grained to conglomeratic. Limestone clasts are abundant in the coarser beds, but vein quartz, sandstone and mudclasts have also been recorded (Francis *et al.*, 1970). One of the sandstones contains a mudrock band with calcrete nodules. Mudstone alternations also occur in the lowest sandstone exposed. Reddish mudstones also occur at the top of the sequence and the highest of these (3 m), which is overlain by the lowest lava of the Clyde Plateau Volcanic Formation, contains decomposed volcanic material. The junction between the mudstone and the lava is irregular.

Interpretation

The three formations of the Inverclyde Group at Gargunnock Burn show stratigraphically and palaeoenvironmentally significant changes in facies. The cyclical sequences of the Kinnesswood Formation were interpreted as fluvial deposits by Read and Johnson (1967) and the product of high-sinuosity channels developed on a gently sloping floodplain. Cross-bedded units reveal a wide range of current directions, but the predominant flow direction is from the north or north-west (Read and Johnson, 1967). The finer mudrocks in the cycles represent overbank deposits of the floodplain. The calcretes have been compared by Read (in Francis *et al.*, 1970) with modern caliche or kankar-type soils and thus indicate an arid or semi-arid climate with a seasonal rainfall. The unusual, dolomitic character of the calcretes may have resulted from secondary replacement of calcite by magnesium-rich pore fluids linked to the deposition of the Ballagan Formation (Francis *et al.*, 1970; Hall *et al.*, 1998).

The finer-grained strata of the Ballagan Formation are interpreted as having been deposited in a wide protected coastal-flat environment (Belt *et al.*, 1967; Francis *et al.*, 1970). The cementstones formed as primary precipitates at times of higher evaporation and elevated salinity when water bodies became isolated. Desiccation cracks show that the wide shallow lagoons occasionally dried out. The facies associations and the interbedding of cementstones and mudrocks indicates a periodically fluctuating environment with an arid to semi-arid climate.

The junction between the Ballagan Formation and the Clyde Sandstone Formation is not exposed at Gargunnock but elsewhere nearby is known to be erosive (Francis *et al.*, 1970). The predominance of sandstones in the Clyde Sandstone Formation indicates a return to a fluvial depositional regime similar to that of the Kinnesswood Formation (Read and Johnson, 1967; Francis *et al.*, 1970) and this is underlined by the presence of calcrete horizons and the presence of limestone clasts that have been reworked both from cementstone and calcrete horizons. Palaeocurrent directions based on cross-bedding dip directions show a wide scatter and an overall flow from a direction between north and west. The return to fluvial deposition in the Clyde Sandstone Formation is an indication of tectonic activity with uplift and rejuvenation of the hinterland, or climate change in the hinterland. Deposition of the formation was terminated by the mid-Dinantian unconformity, which principally affected an elongate belt to the south of the Gargunnock Burn GCR site (Read and Johnson, 1967; Forsyth *et al.*, 1996; Hall *et al.*, 1998; Paterson *et al.*, 1998).

Conclusions

The Gargunnock Burn GCR site is the best exposure of the Inverclyde Group on the northern margin of the Lower Carboniferous outcrop within the Midland Valley of Scotland and to the north of the area principally affected by the mid-Dinantian (late Tournaisian) unconformity between the Inverclyde Group and Strathclyde Group. Significant sedimentological studies have revealed in detail the palaeoenvironmental changes associated with the important transitions from deposition on an arid fluvial floodplain (Kinnesswood Formation) to deposition in hypersaline lagoons on a marginal marine coastal plain (Ballagan Formation) and then, following rejuvenation, a reversion to fluvial deposition (Clyde Sandstone Formation).

TOUCHADAM, STIRLING (NS 761 906)

Introduction

The Touchadam GCR site lies in the valley of the Bannock Burn (NS 761 906), a short distance below North Third Reservoir and about 6 km south-west of Stirling. Here there are faulted outcrops on both limbs of a small easterly pitching syncline, which is a drag feature related to movement along the nearby Wallstale Fault. Sherrif (1796) mentioned the limestone workings at Craigend, by which Touchadam was formerly known, and commented on the quality of the limestone, but the first detailed geological account of the area was that of Dinham (1920). Further details have been published by Dinham (in Flett *et al.*, 1927), Dinham and Haldane (1932), Read (1959) and Francis *et al.* (1970). The sequence shows excellent sections of the Kirkwood Formation and Lawmuir Formation and lower part of the Lower Limestone Formation (resting on the Clyde Plateau Volcanic Formation), which, together with sections of broadly comparable age from **Todholes** (see GCR site report, this chapter) to the south, are of critical significance to the correlation of Strathclyde Group successions in the Stirling–Clackmannan Basin. The upper limit of the Touchadam section is defined by an intrusive contact at the base of the thick Midland Valley Sill.

Description

Details of the succession at Touchadam are presented in Figure 2.25. The basal beds of the Kirkwood Formation (formerly known as the 'Volcanic Detritus') are patchily exposed and neither the basal junction with the lavas nor the upper junction of the unit can be observed. These beds are derived from the re-distribution of material eroded and weathered from the lavas and are very variable in character. They vary in grade from fine clays to conglomerates and are typically highly coloured in green, purple or chocolate hues. Whereas some bands are hard and occasionally calcareous, others are poorly lithified and disintegrate easily. The full thickness is difficult to estimate and, while Dinham's (1920) figure of 30 feet (9.1 m) is most probably too low, Read's estimate (in Francis *et al.*, 1970) of 200 feet (61 m) may be rather large.

Above the Kirkwood Formation and resting on 1.4 m of shales and marls at the base of the Lawmuir Formation is the Productus Limestone (Bannock Limestone G). This hard, grey, biomicritic limestone (1 m) includes bands containing gigantoproductids (*Gigantoproductus*, *Latiproductus* cf. *latissimus*; see Francis *et al.*, 1970) which are often disarticulated and usually orientated convex up. In addition, both solitary and compound (*Siphonodendron junceum*, *Diphyphyllum fasciculatum*) corals occur in bands at the base and towards the top of the limestone. The Productus Limestone is separated from a higher limestone (the Goniatite–Lingula Limestone) by about 12 m of strata which are not completely exposed (Figure 2.25). The exposed beds are shales and light-coloured marls some of which appear to contain fine material derived from weathered lava.

The Goniatite–Lingula Limestone (Bannock Limestone E and F) is a bedded, dark argillaceous limestone (1.1 m) which contains abundant goniatite fragments, orthoceratids, bivalves (*Edmondia*, *Nucula*), *Lingula squamiformis* and other brachiopod fragments and plant remains. Currie (1954) identified the goniatites as *Beyrichoceratoides truncatum* var. H and *Dimorphoceras*. The molluscan shells are typically pyritized. There are also two thin crinoidal bands within the limestone. Above the limestone, a thin shale (0.5 m) containing *Lingula* is sharply overlain by a thick greenish-grey calcareous mudrock (7.5 m), which may be reworked from weathered volcanic material. The mudrock contains horizons of carbonate nodules (Figure 2.25), and towards the base, some of the nodules have a botryoidal appearance and septarian cracks with two stages of calcite infill. Above this mudstone are black pyritous shales (10 m thick). These contain a marine fauna at the base and top but a non-marine fauna of bivalves and *Euestheria* in the middle (Francis *et al.*, 1970). Towards the centre of the shales there is a contorted zone. The basal shale, whose fauna includes *Euphemites urii*, *Sanguinolites* spp., *Myalina* and *Eomarginifera*, contains calcareous and pyritic bands and nodules. The pyrite nodules often show a compound structure and a wide range of crystal forms and textures. Pyrite also occurs disseminated throughout the shale and in small finely crystalline granules.

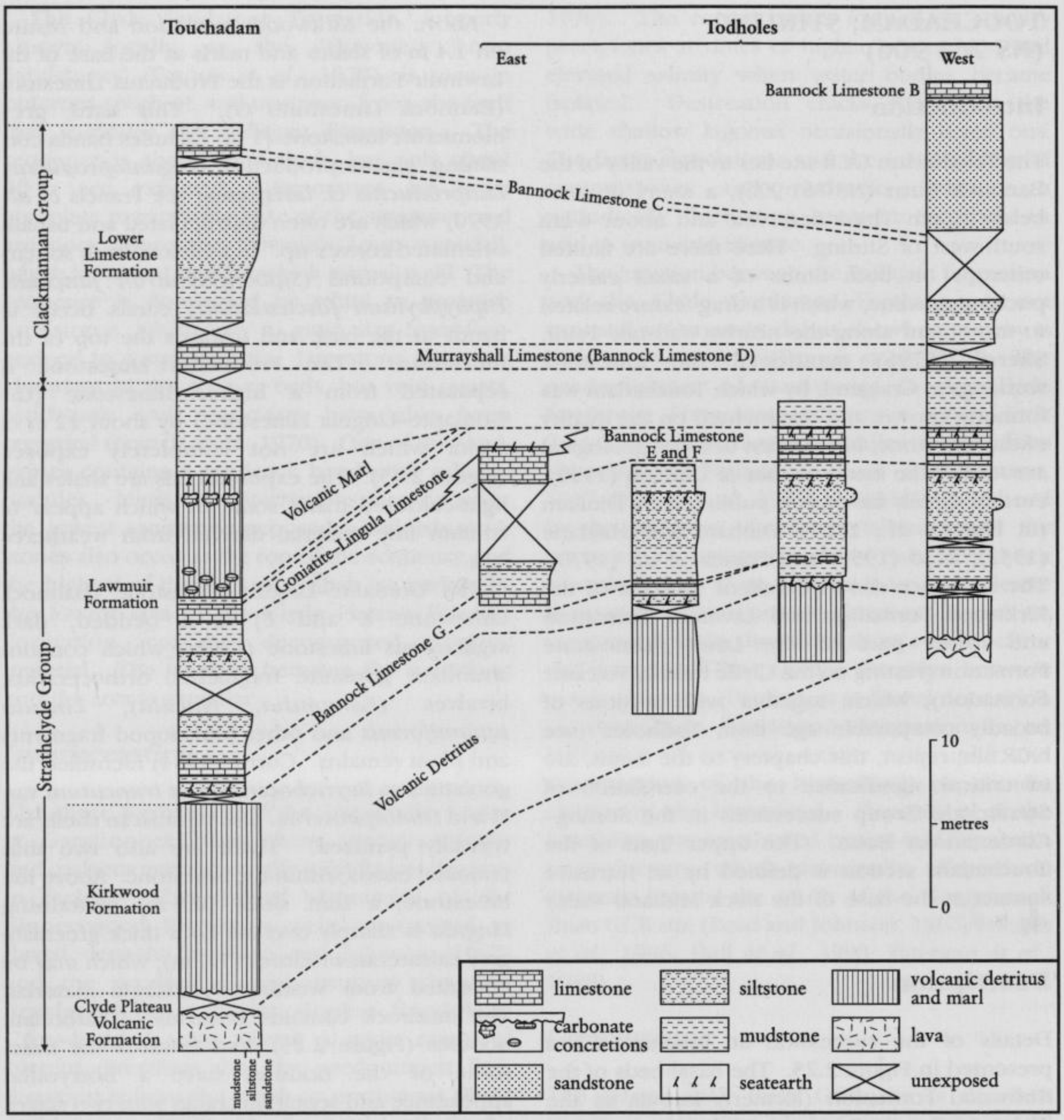


Figure 2.25 Comparative sections of strata at the Touchadam and **Todholes** GCR sites showing the correlation of the principal lithostratigraphical units. Note that the sections at Todholes are each approximately 100 m apart and some 3 km to the south of Touchadam. Based on various sources and including information from Francis *et al.* (1970).

These dark shales underlie the Murrayshall Limestone (Bannock Limestone D, at the base of the Lower Limestone Formation), which has been extensively worked both at the surface (Figure 2.26) and in pillar and stall workings which extend to the south-east under Sauchie Crag. The limestone, which is thought to have been about 1.5 m thick, is no longer exposed but a sample, recovered from the underground workings, was a very dark, pyritous biomicrite containing small crinoid ossicles and brachiopod fragments.

The Murrayshall Limestone is overlain by shales, of which only the top 3 m can be seen. These pass up into siltstone and flaggy yellow sandstones (6 m) with rootlets. Above these and

Figure 2.26 General view of the quarry at Touchadam, where the Murrayshall (Hurlet) Limestone (Lower Limestone Formation, Brigantian) was formerly worked. (Photo: M.A. Whyte.)

below the junction with the sill there is an incomplete section (3.2 m) of shales and a limestone. This limestone (Bannock Limestone C) has been baked by the sill and is a pyritous micritic limestone with colonies of *Siphonodendron*.

Interpretation

The sections in the Bannock Burn at Touchadam are on the western side of the Stirling Basin and provide important information about the transition between the basin and the structural high to the west formed by the extrusive rocks of the Clyde Plateau Volcanic Formation of the Campsie and Touch Hills. Although not fully exposed, the beds of the Kirkwood Formation are thicker at Touchadam than at the nearby sections at **Todholes** (see GCR site report, this chapter). These beds are very largely made up from transported and degraded volcanic material. After the cessation of volcanic activity there was a long period of weathering and erosion, during which the deposits of the Kirkwood Formation were deposited as a unit of variable thickness, which, at least in the Bannock Burn area, thickens markedly eastwards. Regionally, the boundary between the Kirkwood Formation and Lawmuir Formation is markedly diachronous (Browne *et al.*, 1999) and at Touchadam the earliest beds of the Lawmuir Formation are considerably younger than the earliest beds of this formation in the Paisley area (Hinxman *et al.*, 1920; Macgregor *et al.*, 1925). Although the lava landmass appears to have been largely overstepped by the Lawmuir Formation, weathered volcanic material is incorporated into this formation indicating some persistence or intermittent rejuvenation of the volcanic landmass.

The two marine limestone units of the Lawmuir Formation show features of significance to the palaeogeography of the area. The lower of these, the Productus Limestone (Bannock Limestone G), is markedly thicker than at **Todholes** where it thins markedly before dying out completely in the most westerly exposures. With its fauna of corals and gigantoproductid brachiopods this limestone is similar in character to, and correlated with, the Hollybush Limestone of the Paisley area (Hinxman *et al.*, 1920; Dinham and Haldane, 1932; Francis *et al.*, 1970). The upper horizon, the Goniatite–Lingula Limestone, is very different in character from the corresponding limestone (Bannock Limestone E and F) at

Todholes, which has a shelly fauna dominated by brachiopods and bryozoans. The thinner development at Touchadam is interpreted as a deeper-water facies and it is significant that goniatites have been found in the most easterly exposures of this horizon at Todholes, which are also the closest to Touchadam (Read, 1959; Francis *et al.*, 1970). This horizon has been correlated with the Blackbyre Limestone of the Paisley district (Hinxman *et al.*, 1920; Macgregor *et al.*, 1925; Dinham and Haldane, 1932). The character of the Blackbyre Limestone is more similar to the facies developed at Todholes than that at Touchadam but it is interesting to note that 'a thin limestone of Pendleside type' was formerly recorded in it at one locality (Hinxman *et al.*, 1920).

There is no development in the Gonatite–Lingula Limestone at Touchadam of the palaeosol features that are so markedly superimposed on the Bannock Limestone E at Todholes and which mark the position of a disconformity prior to the shales and limestone of the Hurlet (Murrayshall Limestone) Transgression. In the past, the thick 'ashy' mudstone at Touchadam has been inferred to equate with or replace Bannock Limestone E (Dinham and Haldane, 1932; Francis *et al.*, 1970). The 'ashy' mudstone is, however, a product of the disconformity and associated rejuvenation of the volcanic landmass. It thus overlies the surface of disconformity and cannot be equated with any part of the Bannock Limestone E and F sequence, which pre-date the disconformity. Some of its carbonate nodules in the 'ashy' mudstone may be pedogenic and related in time to the processes that modified the upper parts of the limestone at Todholes. A distinctive dark calcite cement in some of these nodules also occurs in Bannock Limestone E at Todholes.

The Murrayshall Limestone is the local representative of the Hurlet Limestone (Dinham and Haldane, 1932; Francis *et al.*, 1970) and its base marks the local base of the Lower Limestone Formation (Browne *et al.*, 1999; and see Figure 2.4). The fauna of the underlying shales (Francis *et al.*, 1970) includes elements of the Macnair Fauna, which is widely distributed at this horizon (Wilson, 1989). Bannock Limestone C is correlated with the Shields Bed of Campsie (Dinham and Haldane, 1932; Francis *et al.*, 1970) but has no equivalent in the Paisley region (Macgregor *et al.*, 1925). The development of this horizon at Touchadam thus provides valuable data for establishing its distribution and palaeogeographical significance (Wilson, 1989).

Conclusions

Situated on the western margin of the Stirling–Clackmannan Basin, this stratigraphically and palaeogeographically significant site provides vital reference sections of the Lawmuir Formation and Kirkwood Formation (Strathclyde Group) which overlap the Clyde Plateau Volcanic Formation, and, in conjunction with the neighbouring GCR site at **Todholes**, is an outstanding locality for the investigation of Lower Carboniferous facies relationships. The remarkable lateral facies changes demonstrated between the Touchadam and Todholes sites and the unique development of facies associated with the stratigraphical discontinuity below the Murrayshall Limestone at Touchadam demonstrate very well the influence of a major structural high (formed by the extrusive rocks of the Clyde Plateau Volcanic Formation) on the development of Brigantian successions in this part of the basin.

TODHOLES, STIRLING (NS 739 877–NS 754 878)

Introduction

The Todholes GCR site, a stream section in the valley of the Bannock Burn (NS 739 877–NS 754 878), 9 km south-west of Stirling, shows Lower Carboniferous rocks, included in the Kirkwood Formation, Lawmuir Formation and Lower Limestone Formation (upper Brigantian), overlapping onto lavas of the Clyde Plateau Volcanic Formation. Above North Third Reservoir the valley of the Bannock Burn essentially runs down to the east, cutting down into the dip-slope of the Carboniferous rocks. Due to irregularities in the stream profile and to minor structural complexities, the sequence is exposed in a series of highly instructive outcrops in the stream and valley sides. In addition to providing an important reference section, these Dinantian rocks exhibit sedimentologically and palaeontologically interesting facies variations (Dinham, 1920; Dinham in Flett *et al.*, 1927; Dinham and Haldane, 1932; Read, 1959; Francis *et al.*, 1970).

Description

The lowest beds in the sequence, the Kirkwood Formation (formerly known as the 'Volcanic Detritus'), are formed from the decay and re-distribution of volcanic material derived from the underlying Clyde Plateau Volcanic Formation (see Figure 2.27). Units within the Kirkwood Formation vary in grade from fine mudstones to conglomerates and are variegated green, grey, brown, yellow or red in colour. While some units contain sedimentary structures and are clearly water-laid, the basal parts are structureless and appear to represent a regolith of decomposed basalt that rests on and passes down into weathered lava. In consequence, although there was a prolonged erosional break between the Clyde Plateau Volcanic Formation and the Kirkwood Formation, the junction may be difficult to locate precisely. The thickness of the Kirkwood Formation is variable but thickens eastwards from 2.4 m to 7 m.

The Kirkwood Formation is discordantly overlain by shales with ironstone nodules which form the first of a series of beds of more normal sedimentary facies at the base of the Lawmuir Formation. These shales vary from 0.3 m to 1.2 m in thickness, and at the top, immediately below an overlying limestone (Bannock Limestone G), contain a marine fauna of bivalves, including *Cypricardella rectangularis*, and fragmentary productoids and spiriferoids. Bannock Limestone G is a grey micritic limestone characterized by the presence of gigantoproductid brachiopods and large solitary corals. It varies in thickness from 0.65 m thick at its most easterly exposure to 0.15 m thick 300 m to the west, and it has apparently thinned to nothing 300 m farther to the west (see Figure 2.25).

About 10 m of shales, mudstones and sandstones separate Bannock Limestone G and a higher limestone unit, which includes Bannock Limestones E and F. The basal parts of the shale immediately above Bannock Limestone G contain marine fossils but higher parts, including the overlying greenish- and yellow-coloured mudstones and sandstones, contain only plant fragments and stigmarian roots and rootlets. These upper beds appear to have a high content of highly weathered volcanic material.

Figure 2.27 General view of the Bannock Burn at the Todholes GCR site showing outcrops of Lawmuir Formation (Brigantian) including Bannock Limestone F and underlying beds. (Photo: M.A. Whyte.)

Bannock Limestones E and F were once treated as separate marine units (Dinham, 1920; Dinham in Flett *et al*., 1927; Dinham and Haldane, 1932) but are now considered to be contrasting parts of a single marine unit (Read, 1959; Francis *et al*., 1970). The lower part (Bannock Limestone F) is a grey-coloured, argillaceous, bedded limestone with shale partings (0.4–1.3 m), which rests on a thin shale with marine fossils (see Figure 2.27). It contains an abundant and diverse fauna dominated by crushed brachiopods including productoids, crinoid ossicles and trepostomous bryozoans. Bannock Limestone E (1.1–1.7 m) contains a similar fauna (Francis *et al*., 1970) but is distinguished by irregular nodules and its creamy white, 'bleached' colour. These latter features are secondary palaeosol features that have been superimposed on the limestone by penecontemporaneous weathering. In places, rootlets and laminated structures, of a possible pedogenic origin, occur in the more massive top of the limestone. The lower limit of the bleaching lies within, and is apparently controlled by, a thick shale parting, which may have acted as an impervious layer. This parting thins and disappears to the east. The most easterly exposure of this horizon also shows a marked change of facies as the upper parts of the exposed limestone (1.5 m), which are irregularly bleached but not nodular, are an argillaceous limestone containing goniatite fragments (0.3 m). These pass up into irregularly bleached shales, the top of which is, unfortunately, not exposed.

The remainder of the succession is less well exposed due to past working of the Murrayshall Limestone (Bannock Limestone D). Bannock Limestones E and F are sharply overlain by shales (4 m) which make up the whole section between these limestones and the Murrayshall Limestone. The basal parts of the shale are dark and pyritous and contain a sparse marine fauna and thin bands of ironstone and limestone. The central parts of the shale are contorted and the upper parts are more calcareous and become increasingly fossiliferous close to the passage into the Murrayshall Limestone. This fauna includes productoids (e.g. *Eomarginifera longispina*, *Dictyoclostus*), other brachiopods (*Spirifer*, *Lingula*, *Orbiculoidea*), bivalves (*Sanguinolites costellatus*), bellerophontids, orthoceratid cephalopods, zaphrentid corals, the trilobite *Paladin eichwaldi*, bryozoans, crinoid ossicles and echinoid remains. A notable feature is that plates, scales and lantern elements of the echinoid *Archaeocidaris urii* may be abundant locally.

The Murrayshall Limestone, at the base of the overlying Lower Limestone Formation, is about 2 m thick, but only the basal 0.3 m, a dark, crinoidal limestone with brachiopod fragments, can be seen. Immediately above this limestone there are shales (1.2 m), with a diverse marine fauna, which pass upwards into barren shales (1.0 m) and flaggy sandstones (0.7 m). A gap (5 m) in the sequence includes the position of the Bannock Limestone C, which may have been economically exploited. Above this, the uppermost beds of the exposed sequence comprise 9 m of sandstone and siltstone. Exposures of quartz dolerite (the Midland Valley Sill) occur a short distance above these, but its contact with the underlying strata is not seen. This gap may include the position of Bannock Limestone B as loose blocks of this, with distinctive laminated intraclasts, can be found in the Bannock Burn a short distance above Todholes Ford (NS 754 878). In the same vicinity there are blocks of sandstone with large plant fragments, which appear to have come from the sequence above the Murrayshall Limestone. The plant fossils recorded by Kidston (1884) probably also came from this part of the sequence.

Interpretation

The locality lies on the eastern flank of the complex volcanic area of the Campsie and Touch Hills. The succession provides significant information about the overlap of these largely basaltic volcanic rocks by later beds of the Kirkwood Formation and Lawmuir Formation and the lower part of the Lower Limestone Formation. After the eruption of the Clyde Plateau Volcanic Formation there was a prolonged period of weathering and erosion, and the earliest bedded strata, the volcanic detritus of the Kirkwood Formation, are almost entirely derived from the reworking of highly weathered lava. The boundary between the Kirkwood Formation and Lawmuir Formation is recognized to be highly diachronous regionally (Browne *et al*., 1999) and the basal beds of the Lawmuir Formation at Todholes are considerably younger than the basal beds in the Paisley region (Hinxman *et al*., 1920; Macgregor *et al*., 1925). The overlying beds of the Lawmuir Formation are deposited in a cyclical sequence and although the marine units provide no evidence to suggest that the sediment was derived directly from the underlying volcanic complex, some of the sandstones and siltstones do appear to include some weathered volcanic material. This emphasizes the progressive and temporally prolonged nature of the overstep of the Clyde Plateau Volcanic Formation.

The first marine horizon recognized at Todholes, Bannock Limestone G, is thinner than at **Touchadam** (see GCR site report, this chapter), and dies out completely within the Todholes outcrop, a feature that underlines the ancient palaeotopography of the region with an eastward-dipping palaeoslope extending from the Clyde Plateau lava pile down into the Stirling–Clackmannan Basin. With its content of corals and gigantoproductids this limestone strongly resembles the Hollybush Limestone of the Paisley district with which it is correlated (Dinham and Haldane, 1932; Francis *et al.*, 1970). Bannock Limestone E and F also show features reflecting this palaeoslope. At Todholes it is predominantly a shelly brachiopod limestone but at the most easterly outcrop a goniatite-bearing facies occurs similar to the goniatite–*Lingula* facies of the equivalent horizon in the more basinward locality of Touchadam. Thus the facies change reflects changes with water depth. This horizon is correlated with the Blackbyre Limestone of the Paisley district (Dinham and Haldane, 1932; Francis *et al.*, 1970).

The palaeosol development that affects the upper part of the combined Bannock Limestone E and F is a widespread feature of the strata between the Blackbyre Limestone and the Hurlet Limestone and representative of a disconformity that can be traced throughout the Midland Valley (Whyte, 1983; Wilson, 1989). At Todholes, palaeosol features are well developed but nearby at **Touchadam** the combined Bannock Limestone E and F is not modified by soil-forming processes but is overlain by a thick marl that has no equivalent at Todholes. This marl may have some volcanic detrital content and may indicate that weathered volcanic material was again being reworked during this interval.

The overlying Bannock Limestone D is correlated with the Hurlet Limestone, and the shales at its base (Francis *et al.*, 1970) include elements of the Macnair Fauna, which are typically found at this horizon (Wilson, 1989). The base of the Hurlet Limestone is the marker for the base of the Lower Limestone Formation. Bannock Limestone C has no equivalent in the Paisley area as marine conditions at this horizon did not penetrate to that area. It is equivalent to the Shields Bed of Campsie and Corrie Burn and the Craigenhill Limestone of Carluke (Dinham and Haldane, 1932; Francis *et al.*, 1970; Wilson, 1989). Its occurrence at Todholes provides valuable information on the distribution of this restricted horizon. Bannock Limestone B is equivalent to the lower leaf of the Blackhall Limestone of Paisley (Dinham and Haldane, 1932; Francis *et al.*, 1970) and also provides valuable information on the distribution and character of this more lagoonal facies of the limestone.

Conclusions

Together with **Touchadam**, the sections at Todholes were described by Dinham (in Flett *et al.*, 1927) as 'the finest sections of Carboniferous rocks in the district'. As well as forming a vital reference section for the Kirkwood Formation and Lawmuir Formation and the lower parts of the Lower Limestone Formation on the western side of the Stirling–Clackmannan Basin, this is an outstanding locality for understanding both local and regional facies variations. This is particularly well illustrated by the contrasting styles of sedimentation evident at this site and the Touchadam site. For example, features indicative of shallow-water deposition and emergence (palaeosols) recognized at specific levels in the succession at Todholes are absent from their time-equivalent horizons at Touchadam.

CORRIE BURN, EAST DUNBARTONSHIRE (NS 681 775–NS 685 794)

Introduction

The Corrie Burn GCR site, lying 3 km north-east of Kilsyth (NS 681 775–NS 685 794), consists of exposures in four small streams, which drain south of the southern flank of the Campsie Fells. Here, faulted against the lavas of the Clyde Plateau Volcanic Formation by the Campsie Fault, are outcrops of the Kirkwood Formation and Lawmuir Formation (Strathclyde Group) and of the Lower Limestone Formation and basal Limestone Coal Formation (Clackmannan Group), which range from late Brigantian to earliest Namurian age (Figure 2.2). This is the finest section of upper Dinantian–lower Namurian strata on the northern side of the Central Coalfield Basin.

The site attracted the attention of many early workers, including Young (1860), Macnair and Conacher (1914), Macnair (1917) and McCallien (1938). Excursion guides have been provided by Bassett (1958) and by Bowes (in Bluck, 1973; in Lawson and Weeden, 1992). Macgregor *et al.* (1925) and Robertson and Haldane (1937) give detailed descriptions of the sequence and these have been brought up to date by Forsyth *et al.* (1996).

Description

Summary details of the site geology are presented in Figure 2.28. The lowest exposed beds here are the uppermost beds of the Kirkwood Formation, which is estimated to be over 55 m thick locally (Macgregor *et al.*, 1925; Robertson and Haldane, 1937). These comprise red and green beds of volcanic detritus derived from the weathering of lavas from the Clyde Plateau Volcanic Formation that are capped by a thin (0.15 m) fireclay. The basal beds of the overlying Lawmuir Formation are not well exposed but are fossiliferous shales (3.4 m) with ironstone nodule bands. The macrofauna and microfauna of these shales formed the basis of an intensive palaeoecological study by McDonald (1966). At the top of this succession, where they contain an abundant fauna of brachiopods (mainly productoids) and bryozoans, the shales become paler and more calcareous as they pass up into the Coral Limestone. This bed is exposed in small outcrops on the valley side of the Corrie Burn and is an irregular (0.6–1.5 m) limestone band with *Siphonodendron* colonies and greenish clay partings. It passes up into the White Nodular Limestone (0.6 m), which has brachiopods and crinoids at the base and abundant rootlets at the top.

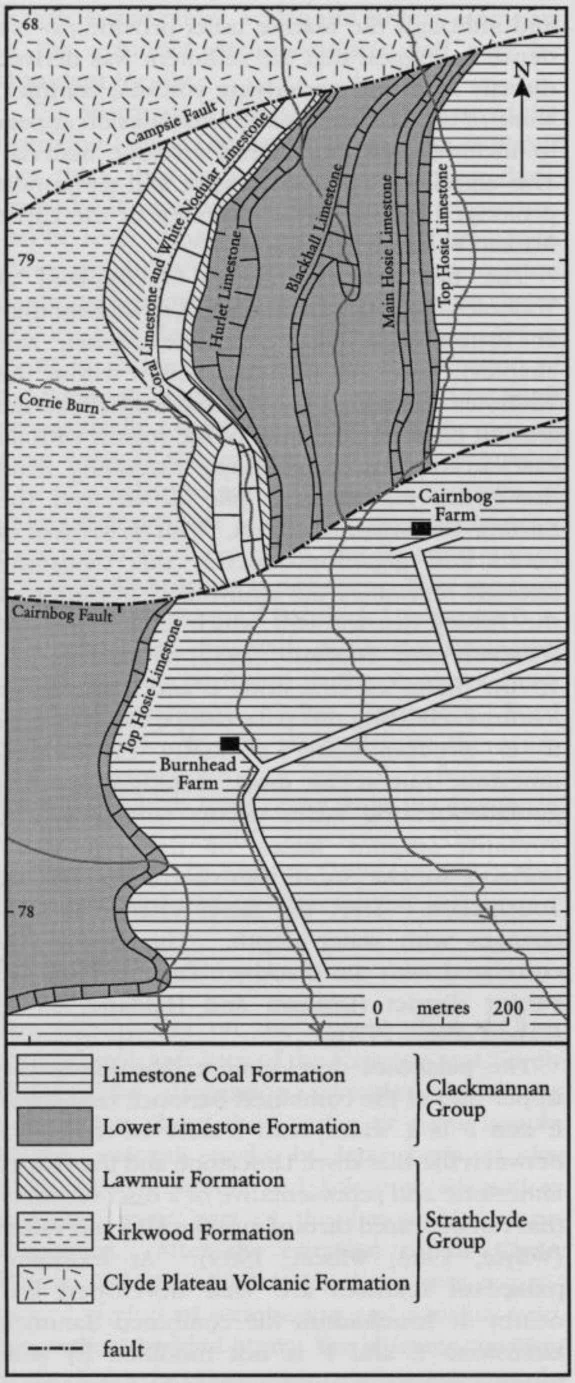


Figure 2.28 Simplified geological map illustrating the distribution of Lower Carboniferous rocks at the Corrie Burn GCR site. Based on various sources and including information from Bassett (1958), Bowes (in Lawson and Weedon, 1992) and British Geological Survey (1992).

The beds between this and the Corrieburn Limestone (= Hurlet Limestone), whose base is the lower boundary of the Lower Limestone Formation, are not now well exposed but include a fireclay (0.4 m) at the base, a thin coal (0.15 m) and fissile shales (4.5 m). The shales contain a layer rich in fish fragments at the base and, higher up, brachiopods, bellerophontids and abundant bivalves including *Actinopteria persulcata* and *Aviculopecten*. The Corrieburn Limestone (6.4 m) is exposed in old quarries to the east of the Corrie Burn. Its lower parts are crinoidal and its upper parts, which are argillaceous, contain an abundant fauna including brachiopods, corals, bryozoans, bivalves and crinoid fragments.

Overlying the Corrieburn Limestone, in the next burn to the east, are shales and ripple-marked sandstones (2.5 m) capped by a decalcified sandy limestone (1.8 m) with crinoid fragments and moulds of shells. Above this are further shales, with a maroon-coloured ironstone, and sandstones (4.0 m) capped by the Blackhall Limestone. The Blackhall Limestone is in two beds separated by a few centimetres of shale. The lower post (0.6 m) is an oolitic dolomite with ostracodes, some intraclasts and stigmarian roots. The crinoidal upper post (0.6 m) also contains small zaphrentid corals. Overlying this, a thick shale sequence (20 m) containing ironstone nodules forms an impressive cliff on the east bank of the middle stream. At its base this shale sequence contains an abundant marine fauna including *Tornquistia youngi*, *Glabrocingulum atomarium*, *Euchondria neilsoni*, *Phestia attenuata* and other forms typical of the Neilson Shell Bed Fauna (Wilson, 1966).

The shale cliff is capped by a sandstone but the beds between them and the Second Hosie Limestone and Top Hosie Limestone are poorly exposed. This poorly exposed section comprises about 25 m of sandstones, siltstone and shale and includes the Main Hosie Limestone and Mid Hosie Limestone and a fireclay. The Main Hosie Limestone and the fossiliferous top of the underlying sandstone are exposed in the eastern stream close to its junction with the middle stream. The Second Hosie Limestone and Top Hosie Limestone are also exposed in the eastern stream. The former is more fossiliferous than the overlying Top Hosie Limestone and the two limestones are separated by fossiliferous shales containing *Posidonia corrugata*, *Tornquistia polita*, and *Sanguinolites costellatus*. *P. corrugata* also occurs in the basal shales of the Limestone Coal Formation immediately above the Top Hosie Limestone. The shales and the Top Hosie Limestone are also exposed in the Wham Glen, which lies west and south of the Cairnbog Fault. It was from these latter exposures in the shale below the Top Hosie Limestone that Craig (1954) made his pioneering palaeoecological studies. Snook (1999) included Corrie Burn in his regional study of faunal associations and facies in the Hosie Limestones.

Interpretation

The volcanic detritus of the Kirkwood Formation is derived from weathering of the lavas of the Clyde Plateau Volcanic Formation, and the section at Corrie Burn provides excellent evidence of the markedly diachronous nature of the boundary between this and the overlying Lawmuir Formation. The marine shales and the Coral Limestone and White Nodular Limestone, which form the base of the Lawmuir Formation, have been correlated with the Blackbyre Limestone of the Paisley and Hurlet districts (Macgregor *et al.*, 1925; Forsyth *et al.*, 1996), though within the Hurlet area the Blackbyre Limestone lies over 100 m above the base of the Lawmuir Formation. Thus deposition of volcanic detritus must have persisted at Corrie Burn long after it had been replaced by more normal (volcanic detritus free) sediments elsewhere. Forsyth *et al.* (1996) have recorded a fossiliferous band within the Kirkwood Formation near Corrie Burn that may correlate with the lower Hollybush Limestone of the Paisley area, and this re-inforces the conclusion that the Kirkwood Formation at Corrie Burn may be laterally equivalent to parts of the Lawmuir Formation in other areas.

The marine unit at the base of the Lawmuir Formation differs from the typical developments of the Blackbyre Limestone in the presence of corals. The white nodular character of the limestones is a secondary bleaching and pedogenic effect linked to the palaeosol and coal, which immediately overlie it and from which rootlets extend down into the limestone. Similar bleaching and nodular developments are know at this horizon at other localities in the Paisley district and at **Todholes** (see GCR site report, this chapter), near Stirling (Macgregor *et al.*, 1925; Wilson, 1989; Forsyth *et al.*, 1996), and indicate a disconformity within the sequence. The remainder of the very attenuated development of the Lawmuir Formation are the basal shales of the Corrieburn Limestone. The fauna of these is important as it is one of the best developments of the Abden (or Macnair) Fauna in Scotland (Macnair, 1917; Wilson, 1989). This fauna provides a useful guide to the position of the Hurlet Limestone and supports the correlation of the Corrieburn Limestone with the Hurlet Limestone though it is considerably thicker and more fossiliferous than that limestone in its type area.

The remainder of the Lower Limestone Formation consists of a number of Yoredale cycles with marine shales and limestones passing up into shales, siltstones and sandstones of deltaic origin. The thin decalcified limestone between the Corrieburn Limestone and the Blackhall Limestone is the equivalent of the Shields Bed of the Campsie district. The occurrence of this horizon at Corrie Burn is of palaeogeographical significance as this marine band is impersistent and is not found to the west of Glasgow. The Blackhall Limestone shows well its bipartite character, with a basal lagoonal facies, which is typical of its development within the Central Coalfield Basin. The shales above the limestone contain a good development of the Neilson Shell Bed Fauna, which is a guide to this horizon (Macgregor *et al.*, 1925; Wilson, 1966, 1989). These shales also contain specimens of goniatites, including *Beyrichoceratoides truncatum*, *Sudeticeras* spp. and *Dimorphoceras marioni*, which indicate a high P_2 age (Currie, 1954). The occurrence of *Posidonia corrugata* in the shales associated with the Top Hosie Limestone is a useful guide to this important horizon, whose top forms the boundary between the Lower Limestone Formation and the Limestone Coal Formation.

The popularity of this site with successive generations of geologists has meant that fossils from it are well represented in collections. The palaeontological lists of Murdoch (1904) include numerous records of species found at Corrie Burn, and Davidson (1851–1886, 1860) described or recorded several brachiopod species from this locality. Other taxa, including the bivalve *Limipecten dissimilis*, the brachiopods *Tornquistia scotica* (paratype material) and *Leptagonia caledonica* and bryozoan material, are also known from the site (Hind, 1896–1905; Brand, 1970, 1972; Bancroft, 1985a,b, 1986a).

Conclusions

Stream and quarry exposures at the Corrie Burn GCR site provide a nearly complete and extremely valuable succession, from the volcanic detritus of the Kirkwood Formation to the base of the Limestone Coal Formation (Brigantian–Pendleian). Situated on the northern side of the Central Coalfield Basin, the character of the marine horizons is important in correlation and in palaeogeographical reconstruction. The limestone beds of the White Limestone, Corrieburn Limestone, Blackhall Limestone and Hosie Limestone yield marine faunas of special and continuing taxonomic, stratigraphical and palaeoecological interest.

BALLAGAN GLEN, STIRLING (NS 573 797–NS 573 804)

Introduction

Ballagan Glen (NS 573 797–NS 573 804) is incised in the southern margin of the Campsie Fells, near Strathblane and about 15 km north of Glasgow. The spectacular exposures in the side of the gorge offer the finest surface section of the Ballagan Formation (Inverclyde Group) in the Campsie district and one of the most significant developments of the Tournaisian 'cementstone' facies in northern Britain. The section also reveals important exposures of the overlying Clyde Sandstone Formation (Inverclyde Group), which lies between the Ballagan Formation and the overlying Clyde Plateau Volcanic Formation (Strathclyde Group). The beds were described by Young (1860) and further details were given by Wallace Young (1867a,b). More recent accounts have been provided by Macgregor *et al.* (1925) and Hall *et al.* (1998).

Description

The gorge of Ballagan Glen runs steeply south parallel to, but opposite in direction to, the small northerly to north-westerly dip of the Carboniferous strata. The beds of the Ballagan Formation, of which 100 m are present, are dramatically displayed in the steep sides of the glen and in downstream sections (Figure 2.29). The base of the formation is not seen, as at the southern end of the section it is faulted against rocks of the Clyde Plateau Volcanic Formation, which have been downthrown to the south by the Campsie Fault.

The Ballagan Formation, formerly known as the 'Cementstone Group' (Macgregor *et al.*, 1925), consists of rapid alternations of cementstones and mudrocks with some sandstones. Young (1867b) counted over 230 separate beds within the gorge sequence. Thin seams and veins of gypsum are also present. The cementstones are usually thin, 0.04–0.3 m in thickness,

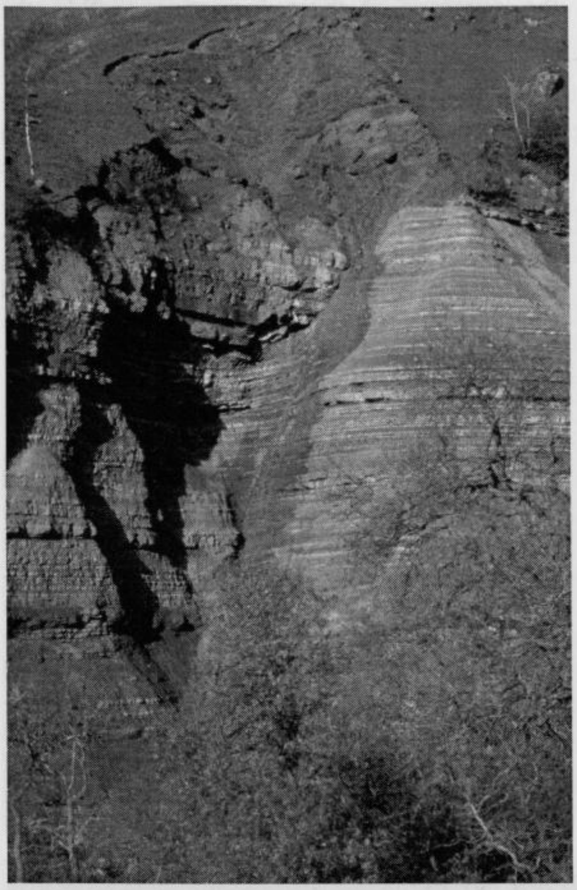


Figure 2.29 General view of the Inverclyde Group (Tournaisian) section at the Ballagan Glen GCR site showing alternating beds of the Ballagan Formation (mainly cementstones and mudstones and a few sandstone bands) overlain at the top of the cliff by the Clyde Sandstone Formation. A prominent fault (top centre-right to bottom centre-left) downthrows to the left. (Photo: C. MacFadyen.)

and may occasionally be nodular. They are generally aphanitic or structureless in character and are dolomitic limestones or dolomicrites. The dolomitic nature of the cementstones was first demonstrated by Young (1867a) and has been consistently supported by later analyses (Macgregor *et al.*, 1925; Hall *et al.*, 1998). The mudrocks, which range from fissile shales to more massive mudstones, are also relatively thin, though usually between 0.3 m and 0.6 m in thickness, and these make up about two-thirds of the formation. They are typically calcareous, grey or greenish-grey in colour and contain varying amounts of silt and sand. Desiccation cracks may occur in the mudrocks. In places, both cementstones and mudrocks may have a secondary reddish colour. The few sandstone beds, which are typically 0.6–1 m thick, are white or red in colour and markedly micaceous. These sandstones are bedded and may show ripple marks. In the lowest 10 m of the sequence, sandstones are more abundant and thicker. They appear to represent a transition from the sandstones of the underlying Kinnesswood Formation, although this latter unit is not exposed at Ballagan because of the effects of the Campsie Fault.

The Clyde Sandstone Formation, formerly known locally as the 'Spout of Ballagan Sandstone' (Macgregor *et al.*, 1925), is predominantly a thick (12 m) white siliceous sandstone with little or no mica. Above this, a thinner (2 m) unit of fireclay with coalified rootlets and sandstone is overlain by the lavas of the Clyde Plateau Volcanic Formation. Fossil plants, including a *Lepidodendron* stem and a possible *Stigmaria*, were recorded from this section by Young (1860), but their exact source horizon is unknown.

Interpretation

Apart from some of the nodular bands, which may be diagenetic precipitates, the cementstones are primary deposits of fine carbonate mud. They and the mudrocks of the Ballagan Formation, both here and elsewhere in Scotland, are interpreted as having been laid down in a wide flat lagoon, or protected coastal flat, with intermittent marine connection and varying salinity (Macgregor *et al.*, 1925; Macgregor, 1930; Belt *et al.*, 1967; Whyte, 1994; Hall *et al.*, 1998). The dolomitic character of the cementstones, the presence of desiccation cracks and the occurrence of gypsum all indicate hypersaline conditions and an arid to semi-arid climate (Belt *et al.*, 1967). Macgregor *et al.* (1925) discussed the origin of the rhythmic alternation between cementstones and mudrocks and related these respectively to drier and wetter conditions. They rightly dismissed a seasonal cycle for the origin of the rhythms and suggested a geographical rather than a climatic oscillation as the underlying cause. The case for climatic variation, however, needs to be reconsidered as the scale of the rhythms and the varying thickness of cycles and their component elements might well reflect a climatic response to orbital forcing and Milankovitch-type cyclicity (House, 1995).

The sporadic sandstones may represent either small channel systems or more widespread sheet-flood deposits. The thicker sandstones towards the base of the sequence are of fluvial origin and indicate that there is a transition from the fluvial-dominated successions of the Kinnesswood Formation into the Ballagan Formation. The sandstones of the Clyde Sandstone Formation indicate a relatively abrupt return to fluvial deposition that may be related to a phase of uplift and rejuvenation of the hinterland prior to the eruption of the Clyde Plateau Volcanic Formation (Hall *et al.*, 1998; Browne *et al.*, 1999). The carbonaceous fireclays at the top of the Clyde Sandstone Formation reflect extensive plant colonization and indicate a change to a more humid climate.

Conclusions

The Ballagan Glen GCR site is the classic section of the Ballagan Formation (Inverclyde Group, Tournaisian) and Young (1860) refers to it as 'presenting one of the grandest specimens of stratification to be witnessed in this countryside'. Although the type section for the formation has recently been re-defined in a borehole section (Browne *et al.*, 1999) Ballagan Glen remains the surface exposure that typifies this lithostratigraphical unit. The sequence is dominated by cementstone–shale alternations, whose cyclical nature probably reflects climatic change in an arid to semi-arid environment. Significantly, features of the overlying Clyde Sandstone Formation (Inverclyde Group) indicate not only a phase of uplift and rejuvenation, but also a change to a more humid environment.

BRIDGE OF WEIR, RENFREWSHIRE (NS 395 656–NS 411 658)

Introduction

The Bridge of Weir GCR site (NS 395 656–NS 411 658) lies 20 km west of Glasgow, and here crops out in the River Gryfe (or Gryffe or Gryfe Water) extending 1.5 km downstream from the town provide the best natural sections of the upper parts of the Lawmuir Formation and much of the Lower Limestone Formation in the west of the Central Coalfield Basin, south of the Clyde. Moreover, these exposures lie at the western extremity of the outcrops of these formations within the Central Coalfield Basin and are the closest remaining outcrops to the Paisley and Hurlet districts, which have in the past provided the standard reference sections for these Brigantian intervals (Figure 2.4). Details of the locality have been provided by Macnair and Conacher (1914), Carruthers and Richey (1915), Macnair (1915), Hinxman *et al.* (1920), Macgregor *et al.* (1925), Forsyth and Wilson (1965), Wilson (1966) and Paterson *et al.* (1990).

Description

The general dip of the succession is to the east, and the Lawmuir Formation is partially exposed in outcrops at the upstream end of the section. These outcrops are complicated by a fault that runs along the bed of the stream and are probably also faulted against lavas of the Clyde Plateau Volcanic Formation (Strathclyde Group). The lowest beds exposed are calcareous shales and limestone bands (2.3 m) of the Hollybush Limestone, which are seen on the north bank of the river. Within the limestone there is a band of *Siphonodendron* and solitary corals, and the gigantoproductid *Latiproductus* cf. *latissimus* is abundant in a fauna that includes other brachiopods (*Gigantoproductus giganteus*, *Eomarginifera*, *Pleuropugnoides* cf. *pleurodon*), sparse molluscs and the echinoid *Archaeocidaris*. Beds immediately above the Hollybush Limestone are not exposed in the River Gryfe. However, about 10–12 m of strata (Macnair and Conacher, 1914), including the positions of the Hollybush Sandstone and the Lady Anne Coal, appear to lie between the Hollybush Limestone and the next exposed horizons, which are associated with the Blackbyre Limestone.

The lowest of these exposures occurs where a small drain enters the river on the southern bank, and shows fireclay and a thin coal (13 cm) separated from the Blackbyre Limestone by 0.3 m of dark shales. The fauna of these shales includes *Actinopteria*, *Posidonia becheri* (indicating an age no younger than P_{1d}) and other bivalves, goniatite fragments, rhynchonellids, productoids, *Lingula* and fish remains. The preservation of some of the fossils is very fine and traces of the original colour banding have been observed in *Lingula* and some of the bivalves (Hinxman *et al.*, 1920). The base of the Blackbyre Limestone here is a dark, calcareous shale (1.2 m) with an abundance of crushed productoids and other brachiopods, crinoid debris and fragments of *Siphonodendron*. The top of the limestone is not seen particularly well, but small outcrops in the river and loose material in the river and in adjacent fields support the view that the top is bleached and nodular, and that it passes up into a greenish nodular fireclay, which may be as much as 5 m thick (Macnair and Conacher, 1914; Forsyth and Wilson, 1965).

A break in the exposures above the Blackbyre Limestone is the result of old workings, and the Hurlet Coal (0.7 m), the Alum Shale (0.3 m) and the bottom bed of the Hurlet Limestone (1.4 m) are not exposed. However, exposures of the interbedded calcareous shales and limestones with crinoid and brachiopod debris (9 m), which make up the upper parts of the Hurlet Limestone are found in the river. The Hurlet Limestone is the lowest horizon within the Lower Limestone Formation, thus these beds and the remaining outcrops in the section belong to this formation.

Above the Hurlet Limestone are dark shales with siderite nodules (4.3 m), fireclay (0.3 m) and a thin coal (15 cm). More dark shales (4.3 m), with *Lingula* at the base and siderite nodules towards the top, occur above the coal and pass up into beds of black and greenish-coloured fireclay. There are polygonal shrinkage cracks in the fireclays, and well-preserved stigmarian roots, which have a complex infill derived from the overlying deposits, extend down into the fireclays. The overlying beds belong to the Blackhall Limestone, which is in two parts separated by shales and other clastics. The lower part (0.3 m) consists of two units of finely bedded ostracode limestone (Figure 2.30) with a thin shale parting. These limestones also contain fish remains, coprolites and spirorbid worm tubes. Between this and the upper part of the Blackhall Limestone are dark shales and greenish mudrocks. The shales contain abundant ostracode and fish debris and one of the mudrocks contains irregular carbonate concretions. The upper part (0.45 m) of the Blackhall Limestone consists of three beds of hard, crinoidal limestone with small solitary corals. On the upper surface of the limestone, at the junction with the overlying shales, irregular oncoidal bodies, developed around orthoconic cephalopods and other shells, are common. The bottom metre of the shale also contains an abundant

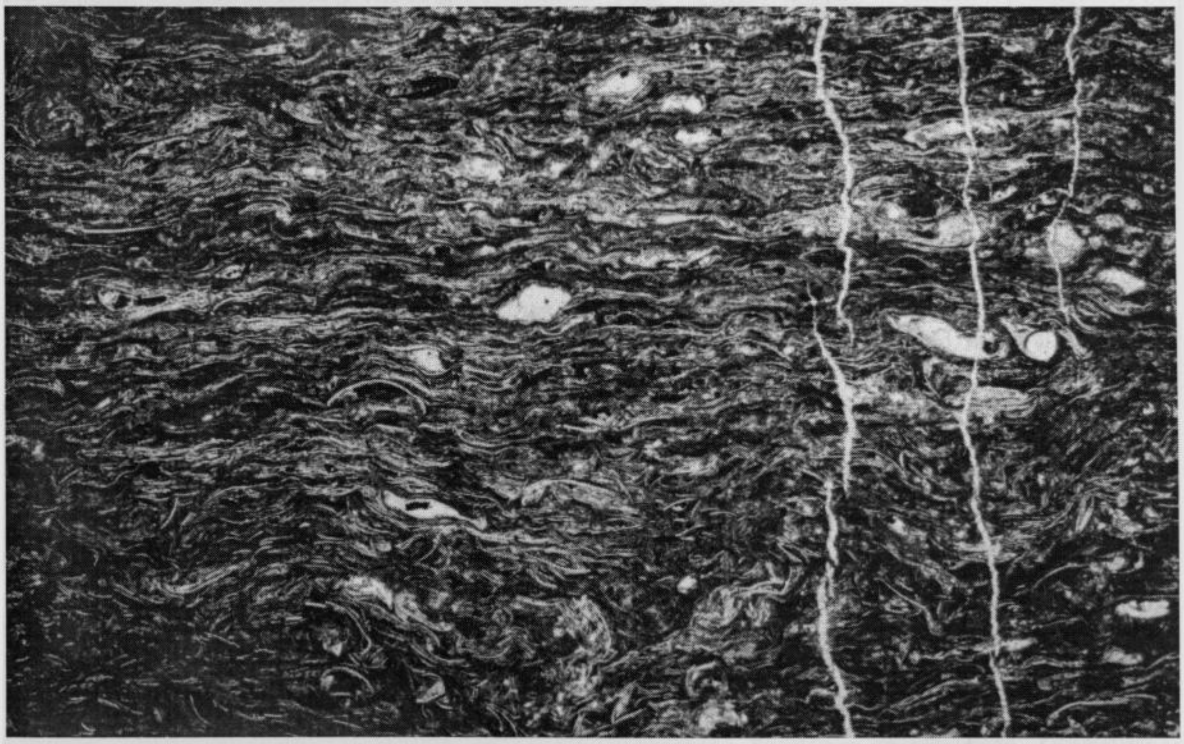


Figure 2.30 Photomicrograph of ostracode valves, shell debris and fish remains in the lower part of the Blackhall Limestone (Lower Limestone Formation, Clackmannan Group, Brigantian). The horizontal field of view is approximately 0.4 mm. (Photo: M.A. Whyte.)

marine fauna, which has been listed by Forsyth and Wilson (1965) and Wilson (1966). Notable elements include the brachiopods *Curithyris urii* and *Tornquistia youngi*, the bivalves *Nuculopsis gibbosa*, *Phestia attenuata* and *Pernopecten fragilis*, cephalopods and gastropods.

The remainder of the succession is dominated by mudrocks and is about 35 m thick. About 15 m above the Blackhall Limestone a group of fireclays and ostracode-bearing ironstone bands has been recorded (Hinxman *et al.*, 1920), and towards the top, above siltstones, there are two marine limestones, which are the Main Hosie Limestone and the Mid Hosie Limestone. These limestones and associated mudrocks were included by Snook (1999) in an analysis of facies and faunal associations in the Hosie Limestones. The Main Hosie Limestone (0.25 m) is a crinoidal limestone with abundant small gastropods at the top. The Mid Hosie Limestone is an argillaceous limestone (0.45 m) with crinoid debris at the base. The shales between the two limestones are not completely exposed but contain trace fossils and, especially below the Mid Hosie Limestone, shelly fossils. The shales (6 m) seen above the Mid Hosie Limestone also contain marine fossils.

Interpretation

The full thickness of the Lawmuir Formation in the Bridge of Weir area is uncertain as the succession below the Hollybush Limestone has never been proved. It is unlikely to be as thick as that near Howwood, 6 km to the south, where nearly 100 m of strata have been recorded below the Hollybush Limestone and include the remarkable Quarrelton Coals and one marine horizon, the Dykebar Limestone (Hinxman *et al.*, 1920; Paterson *et al.*, 1990). The Hollybush Limestone is, however, the first horizon with a rich marine fauna, and the presence of corals and gigantoproductids at Bridge of Weir is typical of its development in the south-west of the Central Coalfield Basin. The lower parts of the Blackbyre Limestone at Bridge of Weir are also comparable in development to other localities although the presence of corals is unusual. The presence of *P. becheri* in the basal shales is indicative of the P_1 Zone. The leached and nodular top of the Blackbyre Limestone has caused some problems in interpretation and in comparison with the Paisley district, where an ostracode limestone, the White Limestone, occurs below the Hurlet Limestone and 12 m above the top of the Blackbyre Limestone. It appears that both the White Limestone and the roof beds of the Blackbyre Limestone are absent at Bridge of Weir (Macnair and Conacher, 1914; Forsyth and Wilson, 1965;) and that the leaching and nodular character is due to soil development and plant growth on a disconformity surface.

Although the Alum Shale at the base of the Hurlet Limestone is not exposed, Macnair (1915) recorded, in loose material, elements of the Abden (or Macnair) Fauna, which is widely developed at this horizon (Wilson, 1989). The Hurlet Limestone in the River Gryfe is very thick compared to its occurrences in the Paisley and Hurlet areas where it is usually less than 2 m thick and overlain by unfossiliferous shales (Hinxman *et al.*, 1920; Macgregor *et al.*, 1925; Forsyth and Wilson, 1965). Its increased thickness at Bridge of Weir appears to be largely due to the incorporation in the limestone of calcareous shales and limestone bands, which are the lateral equivalent of the unfossiliferous shales, and which include the position of the Inchinnan Limestone (Whyte, 1981). Similar thickening of the Hurlet Limestone towards the margin of the Central Coalfield Basin occurs at Howwood, Campsie and Corrieburn (Forsyth, 1978; Whyte, 1981).

The non-marine beds above the Hurlet Limestone include two intervals with siderite nodules, which correlate with the Upper Househill Clayband Ironstone and Lower Househill Clayband Ironstone of the Hurlet district (Hinxman *et al.*, 1920; Paterson *et al.*, 1990), and a coal seam, which may lie at about the same level as the Wilsontown Smithy Coal of Lanarkshire (Hinxman *et al.*, 1920). The outcrop of the Blackhall Limestone at Bridge of Weir has been described as 'incomparably the best exposure in Renfrewshire of a horizon of great interest to the stratigrapher and palaeontologist' (Hinxman *et al.*, 1920). It shows extremely well the salient characters of the horizon, with a lower lagoonal or freshwater limestone and an upper marine limestone overlain by shales with a distinctive marine fauna. This marine fauna is the Neilson Shell Bed Fauna, which forms an excellent guide to this horizon (Wilson, 1966, 1989).

In the strata above the Blackhall Limestone the beds of ostracode-bearing ironstones are a persistent feature of sections throughout the

Glasgow region (Hinxman *et al.*, 1920; Forsyth and Wilson, 1965). North of the Clyde they underlie the position of the Milngavie Marine Band but this dies out southwards and is not found at Bridge of Weir. The Mid Hosie Limestone and Main Hosie Limestone and associated strata are thus the only marine horizons in the upper part of the Bridge of Weir section. The bioturbated siltstone beds below the Main Hosie Limestone may represent the lateral equivalent of the Hosie Sandstone (Paterson *et al.*, 1990).

Conclusions

The Bridge of Weir GCR site is undoubtedly the finest section of the Lawmuir Formation and Lower Limestone Formation (Brigantian) in the west of the Central Coalfield Basin and is the closest available section to the standard reference area from which the stratigraphy of these units was first determined. It includes vital sections of a number of important marine and non-marine marker bands from the Hollybush Limestone (Lawmuir Formation, Strathclyde Group) up to the Mid Hosie Limestone (Lower Limestone Formation, Clackmannan Group).

WAULKMILL GLEN and ROUKEN GLEN, CITY OF GLASGOW (NS 523 584 and NS 549 580)

Introduction

The Waulkmill Glen and Rouken Glen GCR sites are complementary sites that provide the best representative sections of the Upper Limestone Formation (Arnsbergian) in the Central Coalfield Basin. They lie in the Arden area on the south-west outskirts of Glasgow, 9 km from the city centre and 2.5–5 km east of Barrhead. Rouken Glen (NS 549 580), the valley of the Auldhouse Burn, lies in a public park that was described by Macnair (1906) as the best place in the vicinity of Glasgow to 'acquire a knowledge of the leading principles of geology'. Waulkmill Glen (NS 523 584), in which the exposures are more accessible, runs parallel to Rouken Glen and 1.5 km to the west. The two valleys are entrenched in the southern limb of the Arden Syncline, an important E–W-trending fold structure on the southern margin of the Central Coalfield. Descriptions of the sites, as well as summaries of earlier work, are given by Macnair (1906) and Carruthers and Anderson (1908). McCallien (1938) and Bassett (1958), in excursion guides, and Hinxman *et al.* (1920), Macgregor *et al.* (1925) and Hall *et al.* (1998) also give details of the area.

Description

The two localities provide overlapping, but complementary, sections (Figure 2.31) of part of the Upper Limestone Formation (Arnsbergian). The fullest succession is at Waulkmill Glen,

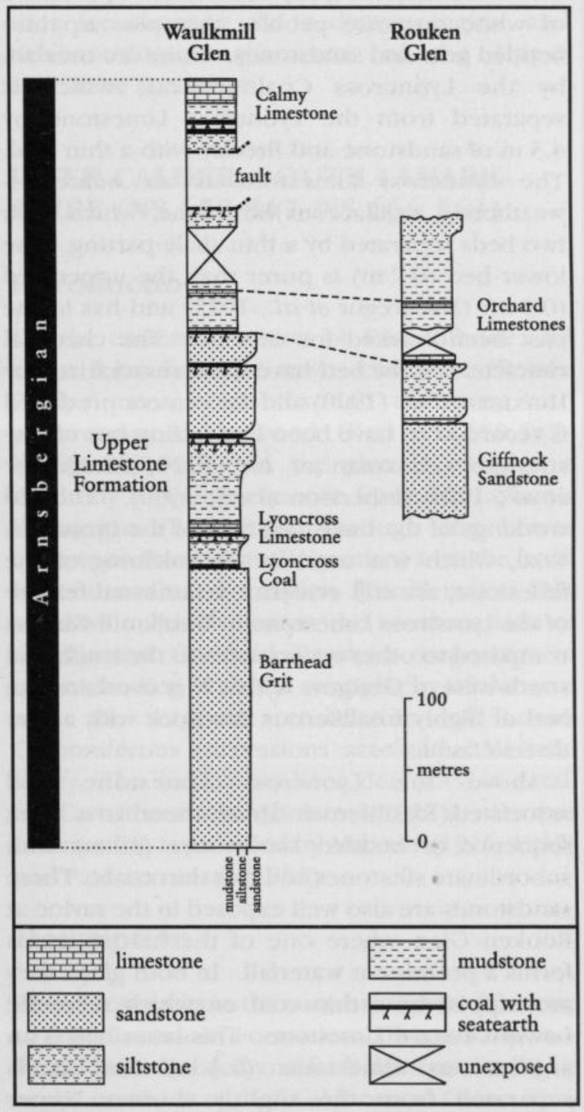


Figure 2.31 Representative sections of the Upper Limestone Formation (Arnsbergian, Clackmannan Group) from the Waulkmill Glen and Rouken Glen GCR sites. After Carruthers and Anderson (1908).

which reveals strata from the Barrhead Grit to the Arden (Calmy) Limestone, including the Lyoncross Limestone and the Orchard Limestones. However, there is a gap in the section where strata between the Orchard Limestones and the Arden (Calmy) Limestone are cut out by a fault. The Rouken Glen exposures provide valuable supplementary outcrops of the missing strata as well as showing clearly their relationship to the underlying Orchard Limestones and Giffnock Sandstones.

The lowest beds exposed at the head of Waulkmill Glen are beds of the Barrhead Grit. These are massive gritty sandstones with bands of white quartzite pebbles that pass up into bedded grits and sandstones. These are overlain by the Lyoncross Coal (0.4 m), which is separated from the Lyoncross Limestone by 4.3 m of sandstone and fireclay with a thin coal. The Lyoncross Limestone is an ochreous-weathering argillaceous limestone, which is in two beds separated by a thin shale parting. The lower bed (0.7 m) is purer than the upper bed (0.3 m) (Macgregor *et al.*, 1925) and has in the past been worked for cement. The chemical characters of the bed have been summarized by Hinxman *et al.* (1920) and the cement produced is recorded to have been fast setting but of low strength (Hinxman *et al.*, 1920; Macgregor *et al.*, 1925; Robertson *et al.*, 1949). The old workings of the limestone and of the Lyoncross Coal, which was used in the calcining of the limestone, are still evident. An unusual feature of the Lyoncross Limestone in Waulkmill Glen as compared to other occurrences to the south and south-west of Glasgow is that it is overlain by a bed of highly fossiliferous mudrock with a very diverse fauna.

Above the Lyoncross Limestone and associated fossiliferous strata there is a thick sequence of bedded sandstones (30 m) with subordinate siltstones and two thin coals. These sandstones are also well exposed in the ravine at Rouken Glen where one of the harder bands forms a prominent waterfall. In both glens they are capped by a thin coal on which rests the Lower Orchard Limestone. This latter bed is an argillaceous limestone (0.3 m) and it is separated from the slightly thinner Upper Orchard Limestone by calcareous shales, which contain abundant fossils only in the upper part close to the upper limestone. Abundant fossils are also found in the shales that overlie the upper limestone.

In Waulkmill Glen there is a gap in the sequence above the Orchard Limestones and then some exposures of dark siltstones and mudrocks outcrop, which are faulted against strata immediately below the Arden (Calmy) Limestone. Although the section in Rouken Glen is also incomplete and, largely because of the presence of a small reservoir, does not extend up to the Arden (Calmy) Limestone, it does show a fine partial section of 20 m of bedded sandstones and sandy siltstones.

The Arden (Calmy) Limestone in Waulkmill Glen is a fine-grained, grey-weathering, argillaceous limestone. The limestone itself is not very fossiliferous, but the overlying shales contain an abundant fauna including productoid and other brachiopods such as *'Dielasma'*, *Composita*, *Spirifer* and *Pleuropugnoides*. In addition, gastropods, a range of orthoconic and coiled cephalopods and fish teeth have been recorded (Bassett, 1958). The beds immediately beneath the limestone are no longer well exposed but included two coals about 0.25 m apart, the Upper Arden Coal (0.3 m) and Lower Arden Coal (0.6 m), and fireclays. The shales between these coals and the Arden (Calmy) Limestone were excavated by Macnair (1906) who recognized the presence in them of *Edmondia punctatella*.

Interpretation

Despite prolonged debate about the position of the sequence within the Arden area (Macnair, 1906; Carruthers and Anderson, 1908), the sections of the Upper Limestone Formation at these two sites provide important evidence of the age relationships between the different strata and of their stratigraphical level at the southern margin of the Central Coalfield Basin (Carruthers and Anderson, 1908). The sections also show a number of features that are regarded as typical of the Upper Limestone Formation.

The Barrhead Grit is an unusually coarse sandstone for this region and its base is known locally to erode down to and through the Index Limestone at the base of the Upper Limestone Formation (Carruthers and Anderson, 1908; Macgregor *et al.*, 1925). Elsewhere, this part of the Upper Limestone Formation contains a number of coal, fireclay and sandstone cycles and the Barrhead Grit appears to have been deposited in a major distributory channel complex, which has cut down through these delta-top deposits (Hall *et al.*, 1998). The depth of the channel and the coarseness of the channel fill may indicate some uplift and rejuvenation of the hinterland. The upward passage from the Barrhead Grit into finer bedded sandstones, fireclays and coals shows a return to delta-top cyclic deposition.

The Lyoncross Limestone is the marine phase of the next cycle. Its development is unusual for the local area but not inconsistent with its regional variation in that it is poorly developed in the east and becomes increasingly well developed towards the west (Wilson, 1967). The overlying sandstones show cyclical sequences with sandstones and thin coals. At this horizon in other parts of the Glasgow district these beds are replaced by more massive channel sandstones with erosive bases, which are known as the Giffnock Sandstones and which have made a good and important building stone (Hall *et al.*, 1998).

The marine phase of the next cycle is represented by the Orchard Limestones, which is the best developed marine horizon in the Upper Limestone Formation throughout the Midland Valley (Wilson, 1967). The cycle continues with an upward passage into shales, siltstones and sandstones capped by fireclays and coals indicative of a delta-front to delta-top transition. These are overlain by the marine strata of the next cycle, the Arden (Calmy) Limestone and associated shales, which here, as is typical of the development in the western part of the Midland Valley (Wilson, 1967), contains a diverse fauna. The occurrence of *Edmondia punctatella* at the base of the limestone is a typical character of the limestone throughout the North Ayrshire Basin and the Central Coalfield Basin (Figure 2.1).

The Arden area has in the past had many quarries and temporary exposures (Macnair, 1906; Carruthers and Anderson, 1908) and both the Lyoncross Limestone and the Orchard Limestones take their names from localities within the basin that are no longer exposed. The Arden Limestone also takes its name from this area, though it is more generally known as the 'Calmy Limestone' throughout the Midland Valley. These long-vanished exposures have in the past provided important sections and a vast amount of faunal evidence. However, because of past controversies as to the exact succession within the basin, it is still difficult to relate all the faunal evidence (e.g. combined faunal lists in Murdoch, 1904; Macnair, 1906) to specific horizons. The Waulkmill Glen and Rouken Glen successions retain the potential to provide more exact faunal information.

Conclusions

The combined sections of strata at Waulkmill Glen and Rouken Glen provide important details of significant parts of the Upper Limestone Formation (Arnsbergian) in the stratigraphically and historically important Arden area of the Central Coalfield Basin. They are the best available sites for this interval in the western part of the Midland Valley and essential sites for showing the sedimentological and palaeontological characters of the Upper Limestone Formation.

RIVER CALDER, SOUTH LANARKSHIRE (NS 658 547–NS 666 563)

Introduction

On the eastern outskirts of East Kilbride and about 2 km from the town centre, the 'Rotten Calder' runs north through the deep and picturesque Calderwood Glen (NS 658 547–NS 666 563). Within the glen is exposed a southerly dipping sequence from the Lawmuir Formation (Brigantian) through the Lower Limestone Formation (Brigantian) into the basal Limestone Coal Formation (Pendleian). This succession, which lies on the southern side of the Central Coalfield Basin, is important in understanding both the stratigraphy of the area and the regional correlation of Lower Carboniferous successions across the Midland Valley. The section has been described in detail by Carruthers and Dinham (1917). Further information is provided by Macnair (1916, 1917) and Paterson *et al.* (1998).

Description

The oldest rocks in the succession, which belong to the Lawmuir Formation (Brigantian), are found in an isolated and fault-disrupted outcrop at the northern end of Calderwood Glen. They are beds of ochreous-weathering, dolomitic limestone and shale, the Netherfield Limestone, with crinoid columnals and productoids. These beds appear to lie stratigraphically about 15 m below the next outcrops, which are of another marine horizon, the Basket Shell Bed, resting on sandstone, coal and fireclay. The Basket Shell Bed has, at the base, calcareous shales with productoids (10 cm) overlain by a lenticular, argillaceous, crinoidal limestone (10 cm). Above these, there are grey shales (1 m) capped by a 5 cm-thick ironstone rib. These latter beds are noted for their fauna and flora (Carruthers and Dinham, 1917) in which cephalopods including goniatites and the bivalves *Dunbarella papyracea* and *Posidonia becheri* occur. Currie (1954) identified goniatites from the Basket Shell Bed as *Beyrichoceratoides truncatum*.

Above the Basket Shell Bed are 4.5 m of shale with thin bands of ironstone, known locally as the 'Whitestone Series' or 'Whitestone Clayband Ironstones'. The shales at the base contain ostracodes, fish scales and coprolites, and although all of the ironstone bands are less than 10 cm thick, they were once worked in the area. The shales pass up into siltstones and a variable sequence of sandstones with mudstone and siltstone bands (5.3 m). Some of the finer beds contain plant remains and a fireclay and coal (0.2 m) occur at the top of this unit. Resting on the coal is a third marine horizon, the Under Limestone. This is a crinoidal limestone (0.8 m) with a thin band (7 cm) of argillacous limestone containing goniatite fragments and plants at its top. The limestone is overlain by shales with fish remains and ostracodes (15 cm) passing up into shales with ironstones (1.5 m), siltstones and sandstones (5.4 m) with fireclays and a bed with irregular pedogenic nodules at the top.

Calcareous shales with marine fossils (0.4 m) overlie the fireclays and pass up into the Main Limestone whose base marks the base of the Lower Limestone Formation. The Main Limestone is a grey crinoidal limestone (1.8 m) and is overlain by shales with ironstone bands (3.6 m), siltstones (4.3 m) and a sandstone (1.5 m). The top of the sandstone contains crinoid debris and is overlain by an un-named sandy crinoidal limestone (12 cm) and an ironstone (12 cm) with brachiopods and bivalves. Above this are shales with ironstones (8.5 m), known as the 'Househill Clayband Ironstones', with, in the centre, two thin ostracode limestones, fireclays and a coal seam (0.3 m) correlated with the Wilsontown Smithy Coal. These are capped by fireclays with rootlets and greenish and yellow marls with irregular carbonate bands and nodules (2 m). The carbonates contain finely bioclastic ostracode debris, some complete ostracode shells, fish remains and lithoclasts. A thin band of dark shale (8 cm), which is pyritous and contains ostracodes and fish remains, separates these from the Wee Post Limestone which is a hard grey crinoidal limestone (0.5 m).

The Wee Post Limestone is overlain by a thick sequence of shales with ironstone nodules (26 m), which contain a marine fauna at the base. Towards the top, the shales become sandier and some thin bands of ostracode limestone are present. They are overlain by the thick Hosie Sandstone (30 m), which is a bedded sandstone with siltstone and fireclay bands and a bioturbated horizon. The top of the sandstone contains crinoid columnals and is sharply overlain by the Main Hosie Limestone (1 m). This is a crinoidal limestone and is separated from the similar Mid Hosie Limestone (0.5 m) by highly fossiliferous shales (1.4 m), which are rich in brachiopods and bryozoans. Above the Mid Hosie Limestone there are partial exposures of shales with ironstone nodules (3 m) which pass up into fireclay (0.5 m) on which there is a thin coal (14 cm). Above this there is a coarse quartzose grit (0.7 m) with a shale parting. The remaining sequence is dominated by shales with two thin limestones, the Second Hosie Limestone and the Calderwood Cementstone or Top Hosie Limestone. The Second Hosie Limestone is a crinoidal limestone (0.3 m) while the Top Hosie Limestone is a compact argillaceous limestone (0.25 m). The shales contain marine fossils and in the beds both above and below the Calderwood Cementstone there are bedding surfaces strewn with valves and shells of *Lingula squamiformis* (Figure 2.32). The shell structure and preservation of these has been studied by Cusak and Williams (1996) and Williams and Cusak (1997). The top of the Top Hosie Limestone marks the top of the Lower Limestone Formation, and the shales above, which pass up into sandstones, lie within the Limestone Coal Formation.

Interpretation

The lowest three marine horizons in the sequence, the Netherfield Limestone, the Basket Shell Bed and the Under Limestone, belong to the Lawmuir Formation and are correlated with the Dykebar Limestone, Hollybush Limestone and Blackbyre Limestone respectively of the Paisley district (Whyte, 1981; Wilson, 1989; and

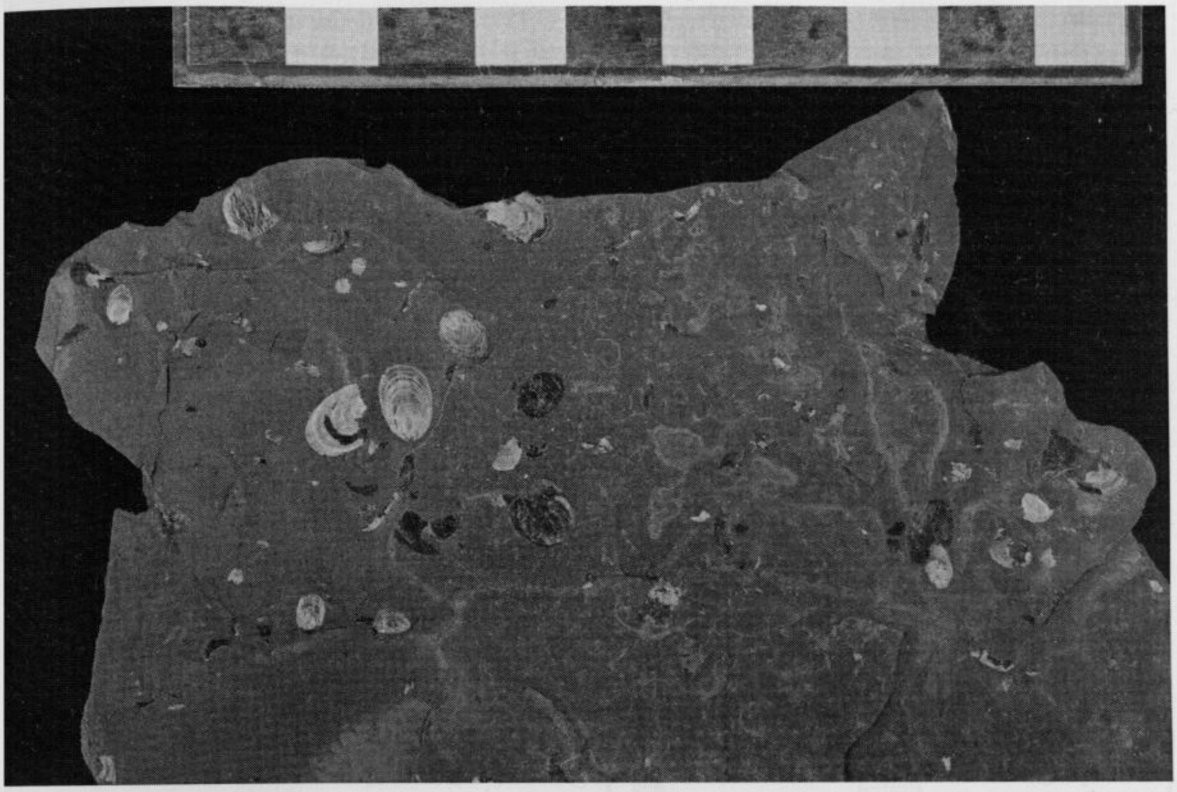


Figure 2.32 Shale containing *Lingula* from the base of the Limestone Coal Formation (Clackmannan Group, Pendleian) overlying the Top Hosie Limestone. The specimen is approximately 6 cm across. (Photo: M.A. Whyte.)

see Figure 2.4). However, all three limestones show some interesting differences from the typical developments of the Paisley area and are thus of stratigraphical and palaeogeographical significance. The Netherfield Limestone in the River Calder appears to be transitional between the ferruginous, argillaceous limestone of Dykebar and the calcareous shales and thin bioclastic limestones of the same horizon at Strathaven. The Basket Shell Bed with its crinoidal and goniatite–bivalve facies is markedly different from the coral and gigantoproductid facies of the Hollybush Limestone of the type area near Paisley. The goniatite–bivalve facies is found elsewhere at this horizon in the southern part of the Central Coalfield Basin and is of significance in correlating this horizon eastwards into the Lothians. The goniatite–bivalve fauna is also particularly significant since it supports a P_1 age for these beds. The Under Limestone resembles the Blackbyre Limestone in its shelly and crinoidal character. However, the direct upward passage of the Blackbyre Limestone into a pale mudstone with pedogenic limestone nodules overlain by fireclay, which is seen in the Paisley district, is not seen in the River Calder, where there are nearly 7 m of strata between the Under Limestone and the overlying zone with carbonate nodules and fireclay. The effects of the disconformity, which these features indicate, are less marked at Calderwood Glen than at Paisley and to the west (Whyte, 1981).

The Main Limestone is correlated with the Hurlet Limestone (Macnair, 1917; Whyte, 1981; Wilson, 1989) and the shales at the base contain representatives of the Abden (or Macnair) Fauna (Carruthers and Dinham, 1917). The un-named limestone between the Main Limestone and the Wee Post Limestone may be correlated with the Craigenhill Limestone of Carluke and the Shields Bed of Campsie (Whyte, 1981; Wilson, 1989; and see Figure 2.4). This limestone is an impersistent horizon and marine conditions did not appear to penetrate to the Paisley area or to the Strathaven area to the south-east of East Kilbride. The strata above are regionally variable (Whyte, 1981) and the presence in the River Calder of a coal seam, which lies at about the position of the Wilsontown Smithy Coal of the eastern side of the Central Coalfield, is significant.

The Wee Post Limestone is correlated with the Blackhall Limestone of the Hurlet district (Carruthers and Dinham, 1917; Macnair, 1917; Whyte, 1981; Wilson, 1989) and in its crinoidal character resembles the upper post of that limestone (Figure 2.4). The lower leaf of the Blackhall Limestone, which is a lagoonal ostracode limestone, may be represented at Calderwood by the marls and carbonate nodules that underlie the Wee Post Limestone. These, however, also contain rootlets and suggest that Calderwood lay close to the margin of the lagoonal area at this time. The shales immediately above the Wee Post Limestone contain, as was first pointed out by Neilson (1874, 1913), the Neilson Shell Bed Fauna (Carruthers and Dinham, 1917).

The Calderwood section as noted by Carruthers and Dinham is important as the only natural section in the area that allows the relationships of the Hosie Limestones to the underlying succession to be established. The Main Hosie Limestone and Mid Hosie Limestone are separated from the Second Hosie Limestone and Top Hosie Limestone by fireclay and coal, which are equivalent to the Lillie's Shale Coal and Hosie Fireclay of the Paisley district. This may mark the position of a regionally important disconformity, and the coarse sandstone above it in the River Calder may indicate uplift and rejuvenation of the source area.

The Hosie Limestones and also the Wee Post Limestone and Main Limestone have in the past been extensively exposed in quarries around East Kilbride, and these attracted the attention of many geologists and collectors including Ure (1793), Davidson (1851–1886, 1860), Young and Robertson (1873), Patten (1885) and Neilson (1895). Many records of plants, foraminifera, corals, annelids, bryozoans, ostracodes, brachiopods, bivalves, cephalopds, gastropods and fish have been documented from these limestones by Murdoch (1904). The surviving exposures of these limestones in the River Calder are thus of great significance. Snook (1999) has carried out a detailed study of the Calderwood succession in his regional analysis of the fossil associations and facies in the Hosie Limestones. From specimens collected from the shales associated with the Calderwood Cementstone in the East Kilbride area, Currie (1954) identified the goniatites *Dimorphoceras* aff. *plicatilis* and a new species of *Cravenoceras* (*C. scoticum*). These are of major stratigraphical significance as they uniquely indicate the presence of the E_1 Zone in Scotland and were used by Currie (1954) to place the P_2–E_1 boundary just below the Top Hosie Limestone.

Conclusions

The River Calder GCR site provides an unusually complete section of the Lawmuir Formation and Lower Limestone Formation and shows the relationships of key horizons within these Brigantian to basal Pendleian strata. The three marine horizons within the Lawmuir Formation can be compared to marine bands in the Paisley district but show some significant differences in facies that are of correlative and palaeogeographical importance. Within the Lower Limestone Formation, valuable sections relating the limestones and intervening clastics are available. The faunas of the marine horizons are of stratigraphical and palaeoecological importance, and a unique feature of the locality are the stratigraphically useful goniatite–bivalve faunas, which indicate that the succession spans from the P_1 to E_1 zones.

PADUFF BURN, NORTH AYRSHIRE (NS 291 562–NS 307 545)

Introduction

Some 3 km west of Kilbirnie and 6 km north of Dalry, the Paduff Burn drains south-east off the Clyde Plateau lavas of the Renfrewshire Hills onto sedimentary sequences at the northern margin of the North Ayrshire (Dalry) Basin. Within its valley (NS 291 562–NS 307 545) is exposed a vital reference section of strata in the Kirkwood Formation and Lawmuir Formation (Strathclyde Group, Brigantian), Lower Limestone Formation (Clackmannan Group, Brigantian) and parts of the Limestone Coal Formation (Clackmannan Group, Pendleian). An early description of features at the site was made by Craig (1869), and fuller descriptions have been given by Macnair (1915), Carruthers and Richey (1915), Richey (1925) and Richey *et al.* (1925, 1930). Further important details of the section have also been described by Richey (1946) and Monro (1999).

Description

A simplified log of the succession is presented in Figure 2.33. The oldest beds are exposed at the upstream end of the section in a fault-bounded exposure. Here limestones and thin calcareous shales of the Broadstone Limestone (5 m) occur above at least 2 m of volcanic detritus (Kirkwood Formation). The limestones contain colonial rugose corals and are replete with large gigantoproductids (*Gigantoproductus giganteus*), many of which are preserved in life position. Orange-coloured marls and shales (2 m) have been recorded overlying the Broadstone Limestone (Richey *et al.*, 1930), but are not currently well exposed. The top of the limestone is penetrated by rootlets and is slightly bleached.

A gap in exposures is followed by outcrops of shales and the overlying Dockra Limestone. The limestone (9 m) is a bedded fossiliferous limestone with thin shale partings and is grey or dark-grey coloured in its lower parts. The uppermost bed of the limestone (1–1.5 m), referred to as the 'White Post', is in contrast a white or creamy-coloured limestone with, in places, a brecciated appearance. It is cut by irregular veins of calcite and penetrated by rootlets, which pipe down some of the overlying green fireclay into the limestone (0.25 m). Richey (1946) noted that these rootlets are often associated with localized dolomitization of the limestone, and red-weathering patches of siderite also occur on the upper surface of the White Post. The top of the Dockra Limestone and the characters of the White Post are beautifully displayed in an extensive series of exposures down the Paduff Burn and have been thoroughly documented by Richey (Richey *et al.*, 1930; Richey, 1946). Richey (in Richey *et al.*, 1930) recognized that the base of the White Post could be slightly transgressive to the underlying beds. He also noted remarkable downward extensions of the base of the White Post (Figure 2.34) which appear as spaced linear features (2–3 m apart) with a wedge or 'V'-shaped cross-section (up to 0.3 m deep) that have the effect of distorting the underlying dark beds into a series of broad flat anticlines and narrow sharp synclines (Richey *et al.*, 1930; Richey, 1946). The amplitude of the folds diminishes downwards and they flatten out and disappear within 2 m.

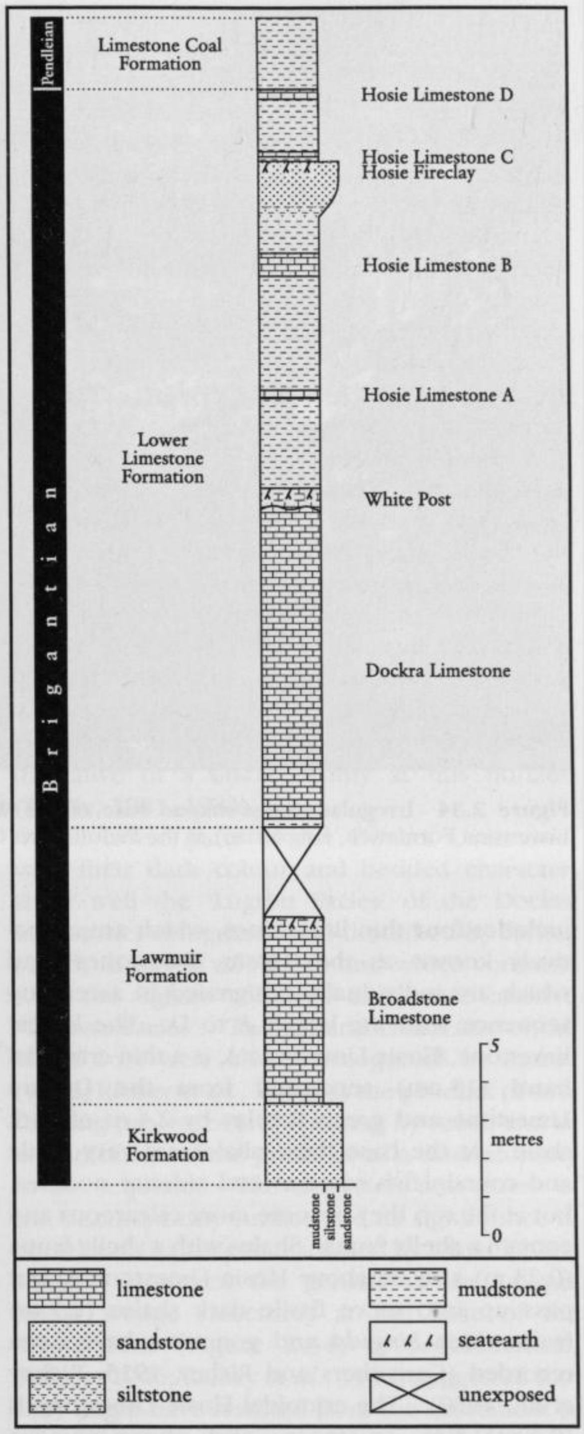


Figure 2.33 Simplified stratigraphy of the Strathclyde Group and Clackmannan Group succession at Paduff Burn. Based on various sources.

A shale-dominated succession overlying the Dockra Limestone is also beautifully exposed in repeated exposures down the Paduff Burn. It

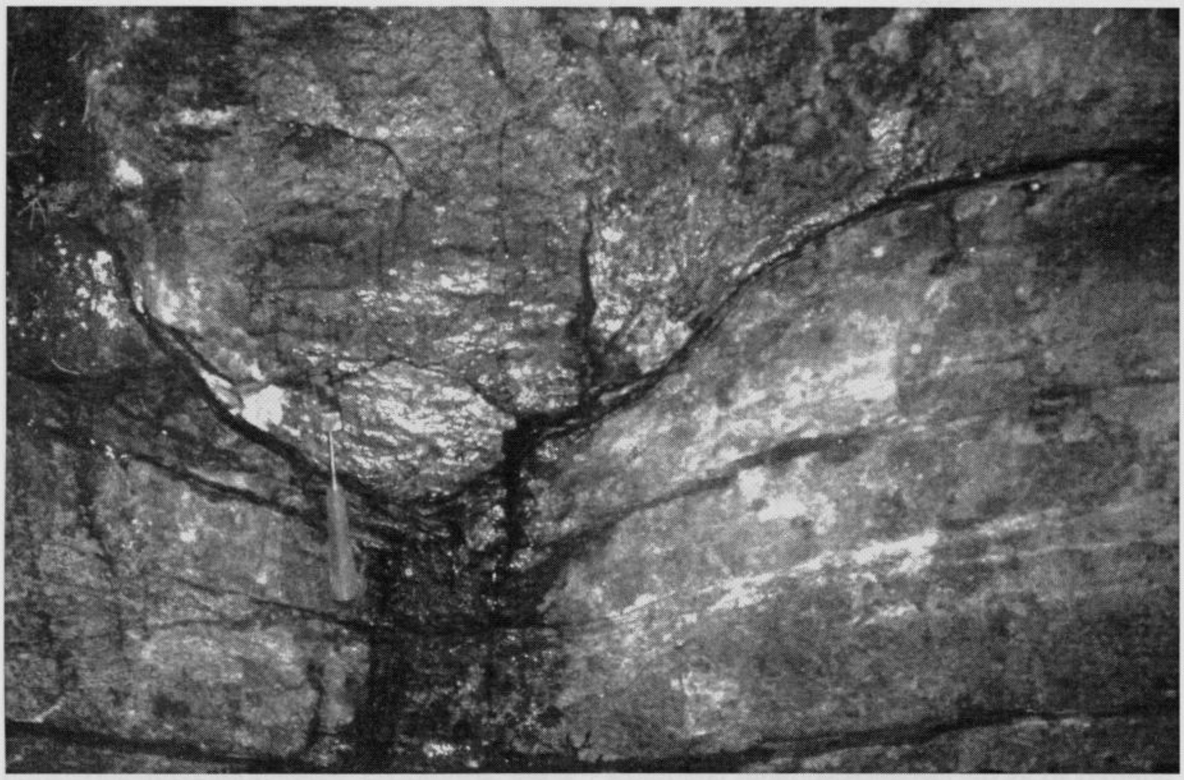


Figure 2.34 Irregular wedge-shaped base of the White Post at the top of the Dockra Limestone (Lower Limestone Formation, Brigantian) at the Paduff Burn GCR site. (Photo: C. MacFadyen.)

includes four thin limestones, which are collectively known as the 'Hosie Limestones' and which are individually designated in ascending sequence with the letters A to D. The lowest limestone, Hosie Limestone A, is a thin crinoidal band (15 cm) separated from the Dockra Limestone and green fireclay by 2.4 m of dark shale. At the base these shales are very fissile and contain fish remains and siderite nodules, but at the top they become more calcareous and contain a shelly fauna. Shales with a shelly fauna (0.23 m) also lie above Hosie Limestone A, but pass up into more fissile dark shales (2.7 m) from which *Lingula* and goniatites have been recorded (Carruthers and Richey, 1915; Richey *et al.*, 1930). The crinoidal Hosie Limestone B (0.6 m) lies on these, and above this, a coarsening-upward succession (3 m), with shales (containing a marine fauna) grading into sandstone, is capped by the Hosie Fireclay (1.5 m). Hosie Limestone C, which is a crinoidal limestone (0.9 m), is separated from the Hosie Fireclay by a thin sideritic band with fish remains and ostracodes and from Hosie Limestone D by 1.5 m of calcareous shales with marine fossils. The latter limestone is a shelly argillaceous limestone, 0.25 m thick. The shales immediately above Hosie Limestone D contain abundant *Lingula* and *Posidonia corrugata* and, while the correlation of lower beds is the subject of some debate, the top of this limestone is generally agreed to mark the top of the Lower Limestone Formation.

The lowest beds of the Limestone Coal Formation are a relatively monotonous, shale-dominated succession (20 m) in which *Lingula* is present. They do, however, include two notable horizons. The first of these, 12 m above the base, is a siderite band (0.3 m), the Dalry Clayband Ironstone; a prominent development in the North Ayrshire sequence. The second, at the top of the section, is a marine unit (1.8 m) with *Sanguinolites costellatus* and rare small productoids in the lower part, and *Lingula* and *Phestia attenuata* in the upper part (Carruthers and Richey, 1915). Beds above the marine band are not well exposed but shales and three ironstones have been recorded (Macgregor *et al.*, 1920) about 10 m above the marine band at the downstream end of the section.

Interpretation

The Paduff Burn succession is an important reference section for the North Ayrshire Basin and a vital section for consideration of the correlation between North Ayrshire and the Central Coalfield. Macnair (1915) regarded the Broadstone Limestone and Dockra Limestone as equivalent respectively to the Hollybush Limestone and Blackbyre Limestone of the Paisley area, while the Ayrshire Hosie Limestones were regarded as equivalent to beds from the Hurlet Limestone to the Top Hosie Limestone (Figure 2.4). Carruthers and Richey (1915) used the Paduff Burn sequence as a standard succession for North Ayrshire and developed a different correlation, which was used in subsequent memoirs (Richey *et al.*, 1925, 1930) and was, for a long time, the generally accepted correlation between the two basins. In this the Broadstone Limestone and Dockra Limestone were correlated with the Blackbyre Limestone and Hurlet Limestone (Carruthers and Richey, 1915). In addition, Hosie Limestone A was correlated with the Blackhall Limestone, and Hosie Limestone B to Hosie Limestone D with the Main Hosie Limestone, Mid Hosie Limestone, Second Hosie Limestone and Top Hosie Limestone of the Central Coalfield. More recently, Wilson (1979) suggested, with some supporting evidence, that the four units of the Ayrshire Hosie Limestones were the equivalents of the four units of the Hosie Limestones of the Central Coalfield and that the Dockra Limestone and Broadstone Limestone were correlatives of the Blackhall Limestone and Hurlet Limestone (Figure 2.4). Whyte (1981) accepted the equivalence of the two groups of Hosie Limestones, as suggested by Wilson (1979), but supported Carruthers and Richey's (1915) correlation of the lower horizons. He further suggested that the absence of the Blackhall Limestone in North Ayrshire was related to the effects of the supra-Dockra Disconformity (Whyte, 1981). This surface is also responsible for the features of the White Post of the Dockra Limestone, which are seen particularly well at a number of localities including Paduff Burn (Richey, 1946; Whyte, 1981).

The Lawmuir Formation comprises the strata between the Kirkwood Formation and the base of the local equivalent of the Hurlet Limestone. Whether the Broadstone Limestone (Wilson, 1979) or the Dockra Limestone (Carruthers and Richey, 1915; Whyte, 1981) is correlated with the Hurlet Limestone, it is clear that the thickness of the Lawmuir Formation at Paduff Burn is not great. In the Paisley to Howwood area and in the centre of the North Ayrshire Basin, much thicker and fuller successions have been proved (Macgregor *et al.*, 1925; Richey *et al.*, 1930; Whyte, 1981; Paterson *et al.*, 1990). Thus the Paduff Burn outcrops provide clear evidence of a prolonged period of erosion and of gradual overlap of the lavas of the Clyde Plateau Volcanic Formation (Richey, 1925; Richey *et al.*, 1930; Whyte, 1981). The thickness of the Kirkwood Formation, in which the weathered products of the lavas have been re-distributed, also seems to be relatively thin in the vicinity of Paduff Burn.

The Broadstone Limestone is found only at one other outcrop in the Kilbirnie part of the northern margin of the North Ayrshire Basin. Its occurrence at Paduff Burn thus provides valuable information about the palaeogeography of this horizon and about the topography of the adjacent lava landmass (Richey, 1925; Richey *et al.*, 1930; Whyte, 1981). The extension of roots into the leached top of the limestone is indicative of a disconformity at this horizon (Whyte, 1981, 1983).

The lower parts of the Dockra Limestone, with their dark colour and bedded character, show well the 'Lugton Facies' of the Dockra Limestone, recognized and described by Richey (1946; Richey *et al.*, 1930) and which contrasts with the lighter coloured and more massive 'Trearne Facies'. The general characters of the White Post were clearly recognized by Richey (1946; Richey *et al.*, 1930) as the product of soil-forming processes and leaching by roots, and as an indication of the presence of a disconformity in the sequence. The characters and extent of the disconformity surface and its significance in correlation have been discussed by Whyte (1981, 1983). However, the genesis of the unique linear wedge structures at the base of the White Post (Figure 2.34) is problematical. Richey (1946; Richey *et al.*, 1930) suggested that they might have resulted from the movement of White Post material into cracks created by down-slope stretching and movement of beds. An alternative explanation is that they might be tepee-like pedogenic structures caused by expansion of the White Post due to the growth of an early diagenetic calcite cement. The unusual inverted nature of the tepees or wedges might be the result of the upper part of the White Post having developed a very strong hard-pan layer, which forced downward expansion of the base. This implies that during pedogenesis the top of the White Post changed from a bed soft enough to allow root penetration to one strong enough to prevent buckling.

The characters of the upper part of the Lower Limestone Formation contrast markedly with the underlying beds in which thick marine beds alternate with fireclays. The Hosie Limestone sequence is dominated by dark and often fissile shales with thin limestones. These reflect an increased overstep of, and decreased influence from, the lava landmasses (Richey, 1925; Richey *et al.*, 1930; Whyte, 1981). The Hosie Limestones fall into two composite marine bands separated by the Hosie Fireclay, which correlates with the Lillie's Shale Coal and Lillie's Sandstone in the Central Coalfield and which may represent another disconformity surface (Whyte, 1981). Paduff Burn is one of the localities examined by Snook (1999) in his study of faunal and facies associations in the Hosie Limestones. The presence of *Posidonia corrugata* in association with Hosie Limestone D supports the correlation of this limestone with the Top Hosie Limestone of Paisley (Carruthers and Richey, 1915; Macnair, 1915; Wilson, 1979; Whyte, 1981). Support for this correlation also comes from the overlying sequence of the Limestone Coal Formation, which has two distinctive horizons. The lower of these, the Dalry Clayband Ironstone, can be correlated with the Johnstone Clayband Ironstone of the south-western Central Coalfield (Macgregor *et al.*, 1925; Richey *et al.*, 1930). The upper horizon, a marine shale, represents the Johnstone Shell Bed, which is the lower and better developed of two marine horizons within the Limestone Coal Formation (Macgregor *et al.*, 1925; Richey *et al.*, 1930). The siderite bands at the top of the section are the Logan's Claybands (Macgregor *et al.*, 1920) and, like the Dalry Clayband Ironstone, these have in the past been exploited in the North Ayrshire area as a source of iron. These beds, with the exception of the marine strata of the Johnstone Shell Bed, were deposited in a brackish or estuarine environment, which contrasts with the more marine strata below.

Conclusions

The natural exposures of the Paduff Burn are the best representative sections of the Lower Carboniferous rocks of the North Ayrshire Basin and show clearly the relationships between the Kirkwood Formation and Lawmuir Formation of the Strathclyde Group (Brigantian) and the Lower Limestone Formation and the lower parts of the Limestone Coal Formation (Clackmannan Group, Brigantian to Pendleian). Together they constitute a vital section for the correlation of successions between North Ayrshire and the Central Coalfield. The development of unique pedogenic structures in the Dockra Limestone make this an excellent site for future sedimentological research.

TREARNE QUARRY, NORTH AYRSHIRE (NS 373 533)

Introduction

Trearne Quarry (NS 373 533) is situated 2.2 km ESE of Beith and 24 km south-west of Glasgow. Until recently, it was an active quarry exploiting the Dockra Limestone (Lower Limestone Formation, Brigantian). The currently exposed sequence reveals reef limestones and associated beds in which there are considerable facies variations. Parts of the sequence are also highly fossiliferous (Figure 2.35). These features make the site of immense interest and value to stratigraphers, palaeontologists and sedimentologists alike. Useful guides to the quarry have been provided by Lawson (in Bluck, 1973) and Burton and Todd (in Lawson and Weedon, 1992), and valuable geological information, based on the uncompleted studies of K.A.G. Shiells, is given in Shiells and Penn (1971). Richey *et al.* (1925, 1930) published good background information about the geology of the general area as well as summaries of previous work, though they present little direct information about the site itself. Aspects of the geology, palaeontology and mineralogy of the site are also reported by Richey (1946), Shiells (1966, 1968, 1969), McIntosh (1974), Browne (1975), Todd (1988) and Monro (1999).

Description

Trearne Quarry has been worked in several bays so there are extensive quarry faces revealing sections which are almost exclusively within the 7–8 m-thick Dockra Limestone. At the north-east end of the quarry and at the south end, in a largely water-filled area of the workings, NW–SE-

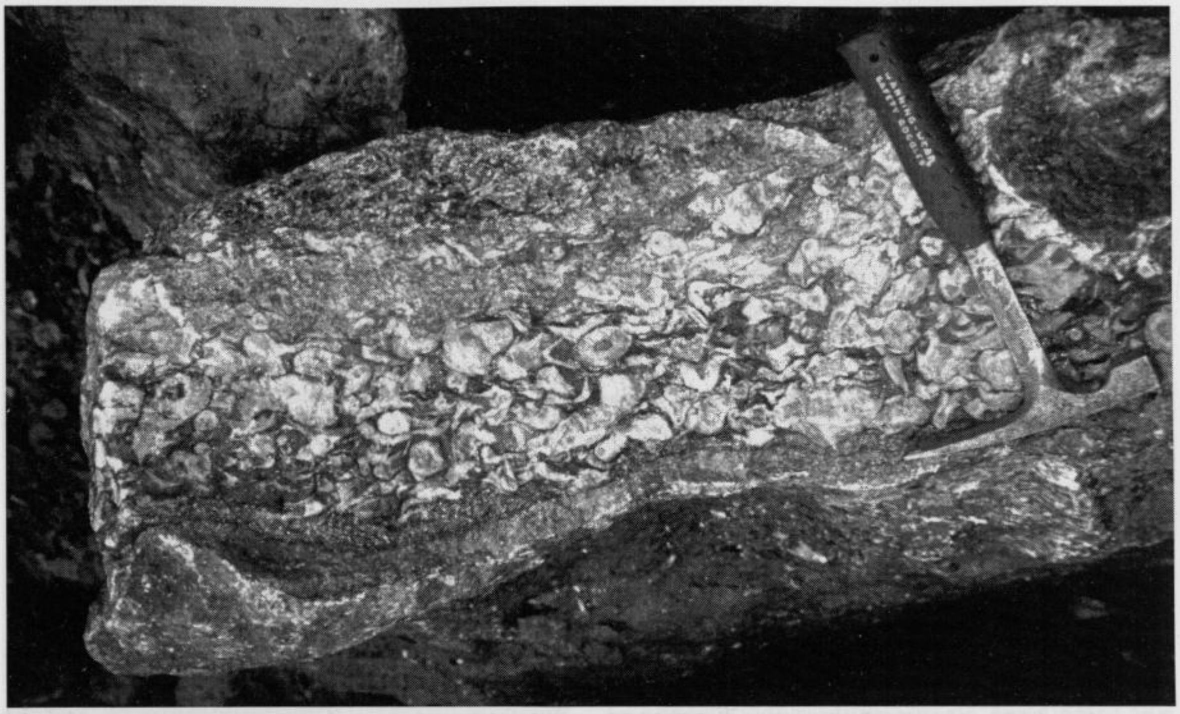


Figure 2.35 Solitary corals in the Dockra Limestone (Lower Limestone Formation, Brigantian) from the Trearne Quarry GCR site. (Photo: C. MacFadyen.)

trending dolerite dykes cut the limestone. A fireclay, coal and dark shale, which underlie the Dockra Limestone, can be seen in a trench north of the quarry entrance. The fireclay (1 m) is light coloured and contains calcareous nodules. It is overlain by the coal, which is up to 12 cm thick and very variable in character with shale and limestone layers within it. Plant stems (*Lepidodendron*) and roots (*Stigmaria*) have been recorded from it as well as nodules of iron sulphides and calcite veins (Burton and Todd in Lawson and Weedon, 1992). The shale shows upward changes in fossil content. At the base (0.24 m) it contains plant remains and scattered fish debris. The central portion of the shale (0.54 m) contains siderite nodules and *Lingula* spp.. Interestingly, both *Lingula squamiformis* and *Lingula mytilloides* are present: the former is more common towards the base and is sometimes preserved in life position, whereas the latter becomes locally more dominant higher in the shale. The top unit within the shale (1 m) contains a marine fauna with *Pleuropugnoides* abundant at the base. The fauna is dominated by brachiopods (*Antiquatonia insculpta*, *Eomarginifera praecursor*, *Martinothyris*, *Spirifer*, *Composita*, '*Dielasma*', *Crania*, *Orbiculoidea*) and bivalves (*Pterinopecten*, *Edmondia*, *Phestia*, *Sanguinolites*) but gastropods (*Straparollus*, *Glabrocingulum*), bryozoans (*Rhabdomeson*), crinoids (*Ureocrinus*) and rare goniatites may also be found. This part of the shale contains pyrite nodules and some of the brachiopod shells are pyritized.

Immediately above the shale, but within the quarry, the Dockra Limestone shows lateral and vertical facies variations (Figure 2.36). To the north, the limestone is made up of more-or-less equal proportions of dark-grey argillaceous limestones and calcareous mudstones in beds up to 0.5 m thick. As the section is followed south the proportion of shale decreases rapidly and limestone beds of a mottled but generally lighter colour make up an increasing proportion of the section. Farther to the south, these pass into more massive but lenticular limestones with, apart from one thicker unit of thin interbedded limestone and shale near the base, a few thin, largely stylolitic, shale partings.

The northern limestones and shales of the Dockra Limestone have a variable bioclast content and distinctive faunas (Burton in Lawson and Weedon, 1992). The many limestone beds frequently contain large specimens

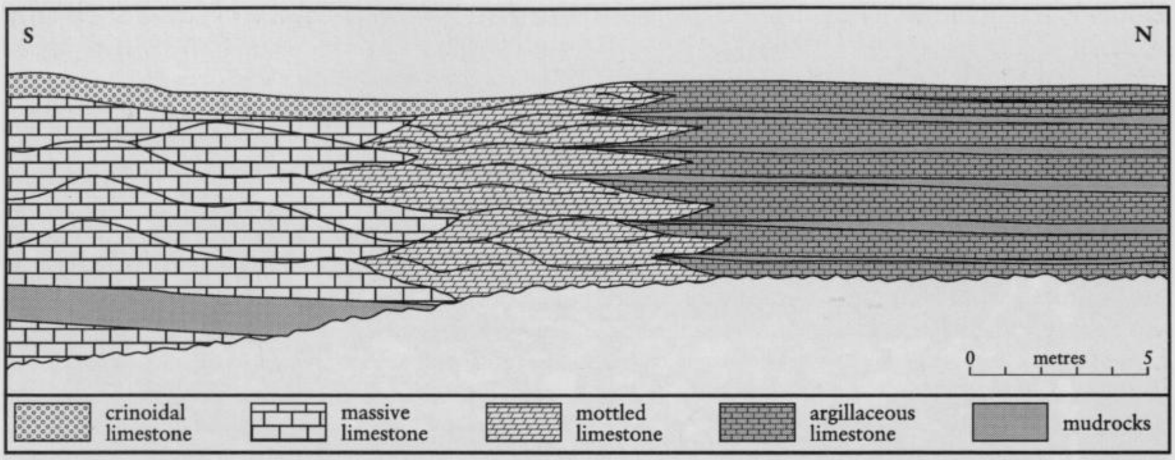


Figure 2.36 Schematic south–north cross-section showing facies distributions in the Dockra Limestone (Lower Limestone Formation, Brigantian) at the Trearne Quarry GCR site, Bathgate. After information principally from Shiells and Penn (1971).

of the flat davidsoniacean brachiopod *Brochocarina trearnensis*, and in addition there are some large gigantoproductids. A range of small productoids, of which *Antiquatonia insculpta* is most common, also occur together with the solitary rugose coral *Aulophyllum*. Crinoid debris is fairly common. In the mudrocks, small solitary corals (zaphrentids, *Fasciculophyllum* and *Allotropiophyllum*) and brachiopods (*Antiquatonia insculpta* and other productoids, *Spirifer*, *Composita*) are common, but large solitary corals (*Caninia*) are also present. Rare but well-preserved specimens of the goniatite *Beyrichoceratoides truncatum* can be found as well as bivalves and trilobites. In some mudrock horizons *Lingula* may be present. Elsewhere there are a few complete crinoids and scattered *Archaeocidaris* plates. To the south, stick and fenestellid bryozoans and long coralla of *Heterophyllia* are present and the brachiopods that become more diverse, include *Kochiproductus* and *Martinothyris*. In the upper parts of the limestone–mudrock sequence, at the northern end of the quarry, an unusual and different fauna with large bivalves (*Pinna* and *Sedgwickia gigantia*) and abundant cephalopods (orthoceratids, nautiloids and goniatites) is developed (Burton in Lawson and Weedon, 1992).

The mottled limestones show a complex internal structure (Shiells and Penn, 1971). They are grain-supported and show complex histories, with microbial mats, early diagenetic cementation and penecontemporaneous erosion producing a complex irregular micro-relief on the sea floor (Burton in Lawson and Weedon, 1992). Concentrations of crinoid debris occur in pockets and as wider patches of long stem lengths. Brachiopod diversity is highest in these beds and forms present include the productoids *Avonia*, *Promarginifera*, *Eomarginifera*, *Pugilis*, *Krotovia*, *Kochiproductus* and *Buxtonia* as well as *Rugosochonetes*, *Martinothyris* and '*Dielasma*'. Among other fossils are specimens of the bivalve *Pinna* in life position and the phosphatic pyramidal shells of the cnidarian *Paraconularia*. The fossils in the limestone are well preserved and because of the early cementation these are uncrushed. In contrast, the associated mudrocks do not show early cementation and have compacted with extensive crushing and deformation of their fossil content (Burton in Lawson and Weedon, 1992).

At the southern end of the quarry, the unit of thin limestone and shale alternations (1 m) is distinguished by an assemblage of partially disarticulated crinoids (*Rhabdocrinus scotocarbonarius*, *Ureocrinus bockschii*) together with bryozoans (*Rhabdomeson*), brachiopods (*Eomarginifera praecursor*) and small zaphrentid corals (Burton in Lawson and Weedon, 1992). The more massive limestones at this end of the quarry contain, especially towards the base, in-situ growths of the colonial rugose coral *Siphonodendron*, which are up to 1 m high and 3 m across. The limestones between the coral colonies contain abundant elongate sponge spicules from the attachment ropes of *Hyalostelia smithi* and show textural evidence of algal precipitates and binding of the sediment (Burton in Lawson and Weedon, 1992). In these limestones there are also bryozoan colonies (*Septopora* and fenestellids), crinoid debris and a reduced variety of brachiopods (*Eomarginifera longispina*, *Krotovia spinulosa*, *Echinoconchus punctatus*, *Brachythyris*). The brachiopod shells often contain geopetal infills, which are out of alignment with the bedding and suggest some post-depositional disturbance of the shells. The *Siphonodendron* colonies become smaller and scarcer upwards, while solitary corals such as *Dibunophyllum*, *Caninia* and *Aulophyllum* become more common and may occur in clusters, which have been washed together. At up to five levels within these limestones there are irregular lenses (up to 7 cm thick) made up of coral and brachiopod debris. Locally, at one part of the face, flat chaetetid sponge bases can be seen growing on the irregular and hummocky surface of a bed of bioclastic debris. Broken and stacked gigantoproductid valves are also present.

Another band of overturned and disarticulated gigantoproductid valves is present below the thick bed of crinoidal grainstones that caps this part of the sequence. The crinoidal limestones contain not only long lengths of randomly orientated crinoid stem but also spines of the brachiopod *Eomarginifera*, fish teeth (*Petalodus*) and fan-shaped colonies of fenestellid bryozoans (Burton in Lawson and Weedon, 1992). The uppermost surface of this bed is marked by yellow-coloured crinoidal limestones with stigmarian roots (Lawson in Bluck, 1973; Burton in Lawson and Weedon, 1992). A further, and possibly separate, surface of emergence (palaeokarst) lies about 0.3 m lower in the sequence.

In addition to the intrusion of the dykes at the northern and southern ends of the quarry, which was accompanied by localized decalcification and baking of the country rock, there is extensive veining of the limestone. These veins have a complex mineralized infill and the following minerals are recorded: calcite, quartz, dolomite, barite, strontianite, fluorite, pyrite, chalcopyrite, millerite (Todd in Lawson and Weedon, 1992). Many of these minerals can be found as secondary mineralizations in the cavities within brachiopod shells. Chert bands are developed in the northern part of the quarry and locally there is some silicification of fossils (Richey *et al.*, 1930; Lawson in Bluck, 1973; Burton in Lawson and Weedon, 1992).

Interpretation

Trearne Quarry lies close to the north-eastern margin of the North Ayrshire Basin (Richey *et al.*, 1925, 1930; Whyte, 1981). During Brigantian times, the lavas of the Clyde Plateau Volcanic Formation made an upland or island area to the east (Figure 2.3c) against which the sedimentary successions of the Lawmuir Formation and the Lower Limestone Formation thinned (Richey, 1925; Richey *et al.*, 1925, 1930; Whyte, 1981). At Trearne, the Dockra Limestone is 7–8 m thick, but to the east it thins to zero within 8 km. A shallow strait probably also existed to the north between the North Ayrshire Basin and Central Coalfield Basin (Richey, 1925; Richey *et al.*, 1930; Whyte, 1981).

The varied assemblage of carbonate and palaeontological facies developed at Trearne reflects and provides vital detail of this palaeogeography. The basal shales provide valuable evidence of the marine trangression, with a progression from a peaty soil and swamp facies through a brackish-water facies containing *Lingula* to a more fully marine facies with diverse faunal assemblages. The association of the two *Lingula* species is interesting and their distribution suggests that *Lingula squamiformis*, which appears earlier in the bed, may have been more tolerant of reduced salinity than *Lingula mytilloides*.

The thin shales and limestones at the base of the Dockra Limestone at the southern end of the quarry have been interpreted as a tiered community of crinoids, bryozoans and brachiopods living in water depths of about 10 m (Burton in Lawson and Weedon, 1992).

The massive limestones and the mottled limestones correspond respectively to the Reef Limestones and the Multicomponent Mudstones of Shiells and Penn (1971), and collectively to the Trearne Facies of Richey (1946; Richey *et al.*, 1930). The Reef Limestones are reef-mound limestones with small local reliefs and with corals, bryozoans, sponges and algae contributing to the buildup. The Multicomponent Mudstones represent the flank beds of these buildups. The associated fauna in these beds is largely preserved at the site at which it lived and some of it is in life position (Shiells and Penn, 1971; Burton in Lawson and Weedon, 1992). However, in both the Reef Limestones and Multicomponent Mudstones, there is evidence of shell disturbance, and localized debris beds indicate at least occasional higher energy events. Water depths may have been shallower than those of the underlying tiered crinoid community, and the upward replacement of colonial corals by solitary corals in the massive limestones may indicate a shallowing trend (Burton in Lawson and Weedon, 1992). The crinoidal grainstones at the top of the succession also indicate shallower and more turbulent conditions.

The dark limestones and shales of the northern part of Trearne Quarry correspond to the Lugton Facies of Richey (1946; Richey *et al*., 1930) and to the Bedded Limestone and Shale of Shiells and Penn (1971). The presence of some complete crinoids and clumps of *Archaeocidaris* plates, which represent the undispersed remains of individual echinoderms, indicate quiet depositional conditions, as does the preservation of bivalves in life position or with valves splayed but still associated. The infaunal bivalves, corals with radicular structure (*Allotropiophyllum*) and the flat thin platy valves of *Bochocarina trearnensis*, for which this is the type locality (McIntosh, 1974), indicate a very soft bottom substrate. The shales and limestones were deposited on the shoreward side of the reef mounds in a protected lagoonal environment. The scattered occurrences of *Lingula* indicate more brackish conditions and oscillations of the Dockra Limestone shoreline.

Shiells (Shiells, 1966, 1968, 1969; Shiells and Penn, 1971) made a special study of the diverse productoid fauna, noting its distribution and preservation within the limestones and shales. Geopetal fills and unbroken long spines indicated that many of the productoids were still in life position even though hinge lines might be inclined (Shiells and Penn, 1971). Two species, *Promarginifera trearnensis* and *Kochiproductus coronus*, and their functional morphologies were described in detail, based on type material from Trearne (Shiells, 1966, 1968, 1969).

The crucial palaeontological importance of Trearne Quarry has been underlined by the unique soft-bodied fauna that has recently been discovered at the site. This highly significant and extremely exciting discovery is currently being worked on by C.J. Burton and N. Clark (Glasgow University), who are also describing new sponges from the locality (C. Burton, pers. comm., 2000).

The well-defined palaeosol development at the top of the Dockra Limestone at Trearne is a common though not ubiquitous feature of this horizon in North Ayrshire (Richey, 1946; Richey *et al*., 1930; Whyte, 1981). Macnair (1915), influenced by this feature, suggested that the Dockra Limestone was equivalent to the Blackbyre Limestone of the Central Coalfield, which has also frequently been modified by an overlying palaeosol. However, Carruthers and Richey (1915; Richey 1925; Richey *et al*., 1930), using other criteria, developed a correlation in which the Dockra Limestone was equated with the Hurlet Limestone of the Paisley district. This latter correlation was widely accepted until recently when Wilson (1979), using new fossil evidence, suggested an alternative correlation in which the Dockra Limestone was equated with the higher Blackhall Limestone. Although accepting parts of this correlation, Whyte (1981) has argued that the fossil evidence is not unequivocal and that the Dockra and Hurlet limestones are equivalents (Figure 2.4). The absence of an equivalent of the Blackhall Limestone in North Ayrshire is considered by Whyte (1981) to be related to the prolonged overstep of the disconformity surface above the Dockra Limestone. Wilson (1989) and Whyte (1981) present palaeogeographical maps based on their differing views of the correlation of the Dockra Limestone.

Conclusions

Trearne Quarry provides a unique section through a highly fossiliferous Brigantian reef complex that developed in the Dockra Limestone towards the north-eastern margin of the North Ayrshire Basin during late Dinantian times. The complex variations in sedimentary facies and rich faunas at Trearne make this one of the most valuable combined interest sites in the Midland Valley and one of particular significance to the stratigrapher, sedimentologist and palaeoecologist. It is the type locality for several invertebrate taxa and, as recent exciting discoveries have amply demonstrated, a site of great palaeontological potential. It also provides vital information for the correlation of Brigantian successions between the North Ayrshire Basin and Central Coalfield Basin.

LINN SPOUT, NORTH AYRSHIRE (NS 283 485)

Introduction

The natural exposures in the gorge and waterfalls on the River Caaf at Linn (or Lynn) Spout (NS 283 485), 1 km south-west of Dalry in Cunninghame, provide an excellent exposure of the Upper Linn Limestone and associated shales. 'Upper Linn Limestone' is the local name for the Calmy Limestone of the Upper Limestone Formation (Clackmannan Group, Arnsbergian). Richey *et al.* (1925, 1930) have provided general details of the site, which is primarily famous for its rich and unusual fauna. Descriptions and chemical and petrographical information are given in Robertson *et al.* (1949) and Muir and Hardie (1956).

Description

At Linn Spout the medium-bedded Upper Linn (Calmy) Limestone (*c.* 18 m thick) forms a series of small waterfalls in the gorge (Figure 2.37). The slightly argillaceous limestone beds are finely bioclastic. They are grey when fresh but weather to a yellowish colour. Bedding surfaces are slightly irregular and limestone beds are bioturbated and recrystallized. Associated with the limestone are about 5 m of fossiliferous calcareous mudstones. At the base there is a thin band of dark shale which contains an abundance of the bivalve *Edmondia punctatella*. Beneath this is a coal, the Broadlie Coal, which was mined from an adit a short distance below Linn Spout.

The limestones and, to a greater extent, the calcareous shales contain a fauna dominated by brachiopods and crinoid fragments but in which, significantly, a diversity of other forms have also been recorded, including small solitary and colonial rugose corals, bivalves, cephalopods, bryozoans, foraminifera, sponges, conodonts and trilobites.

Interpretation

The characteristics of the Upper Linn Limestone are consistent with its having been deposited in an open marine, shallow-shelf environment. Wilson (1967) noted that in the Calmy Limestone the faunas were more varied in the Central Coalfield than in Midlothian and East Fife. The diversity of the fauna of the Upper Linn Limestone suggests that this trend may also extend into North Ayrshire and that it would repay further palaeoecological investigation.

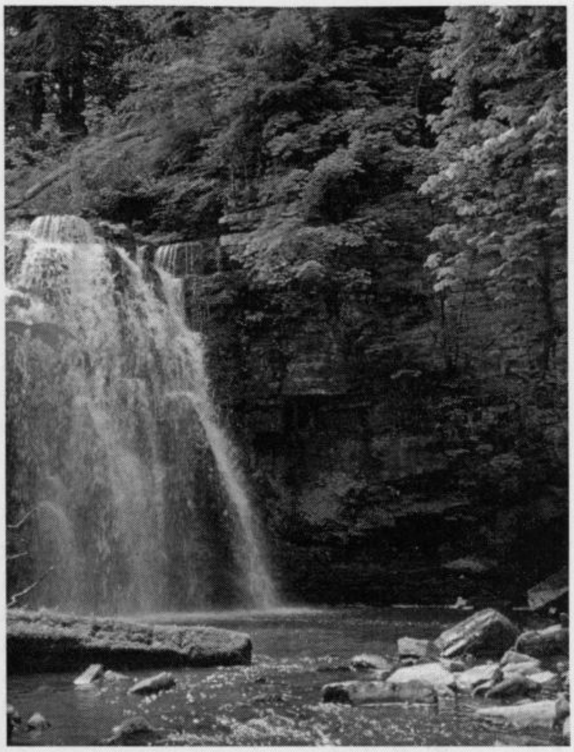


Figure 2.37 Waterfall section of the Upper Linn (Calmy) Limestone (Upper Limestone Formation, Clackmannan Group, Arnsbergian) at Linn Spout, near Dalry. (Photo: C. MacFadyen.)

The brachiopods recorded from the site include productoid, spiriferoid, terebratulid and rhynchonellid forms; in addition, Brand (1972) recorded *Leptagonia* and McIntosh (1974) recorded the orthotetoid *Brochocarina wexfordensis*. Several epifaunal pteriomorph bivalves have been recorded as well as infaunal bivalves such as *Cypricardella*, *Parallelodon* and *Sanguinolites*, and the three palaeotaxodont species, *Nuculopsis gibbosa*, *Phestia attenuata* and *Palaeoneilo laevirostrum* (Murdoch, 1904). The band of the bivalve *Edmondia punctatella* at the base of the sequence is a characteristic feature of this horizon in North Ayrshire and the Central Coalfield, but is less common and developed differently in Midlothian and East Fife (Wilson, 1958, 1967).

It is, however, other fossil groups that have attracted most attention. Hinde (1887–1912) based several sponge descriptions on material from the Upper Linn Limestone, and Smith

(1900) recorded conodonts from this locality in his pioneering studies of Scottish Carboniferous conodonts. Material from Linn Spout was included by Currie (1954) in the specimens on which she based both the genotype of the goniatite *Cluthoceras*, *C. truemani*, and a second new species *C. neilsoni*. Later, however, Riley (1996) demonstrated that this genus is a junior synonym of *Beyrichoceratoides*. Linn Spout is the type locality for the trilobite subspecies *Paladin eichwaldi paralis* (Reed, 1943; Osmólska, 1970). The limited rugose coral fauna (which includes the type material of *Dibunophyllum linnense*) is also significant as one of the youngest faunas of its kind in the British succession. Hill (1938–1941, 1948) attached considerable importance to this and considered that the Upper Limestone Formation corals formed a distinct group, which she referred to her Coral Zone 4 (Hill, 1938–1941). The colonial species found at Linn Spout, *Aulina rotiformis*, has also been recorded from China (Hill, 1938–1941) and is particularly important for understanding coral palaeobiogeography and evolution (Hill, 1948).

Conclusions

The sequence at Linn Spout provides an outstanding section of the richly fossiliferous Upper Linn (Calmy) Limestone (Arnsbergian Upper Limestone Formation), a marine unit with a fauna of immense taxonomic and palaeoecological significance. It is the type locality for a variety of invertebrate fossil taxa (genera and species) including sponges, conodonts, trilobites and cephalopods, and also contains interesting brachiopod, bivalve, bryozoan and foraminiferan faunas. Species present are of great value in palaeogeographical reconstructions for this part of the Carboniferous System, both on a regional and on an international scale.

CORRIE SHORE, ARRAN, NORTH AYRSHIRE (NS 022 444–NS 026 433 and NS 025 436)

Introduction

The Corrie Shore GCR site, on the Isle of Arran, provides a spectacular and very accessible section of Tournaisian–Arnsbergian strata and is, arguably, one of the most complete sections of Lower Carboniferous age in the west of Scotland. The section crops out for 1 km along the shore from just north of the village (NS 022 444) to about 50 m south of the Corrie Hotel (NS 026 433). The rocks have a southerly dip and the base of the succession is thus exposed at the northern end of the outcrop and the youngest beds are exposed at the southern end of the section. Close to Corrie Harbour (NS 025 436) the site is extended inland to include outcrops within an old quarry. The section has been described in detail by Tyrrell (1928). It has also been described in several excursion guides (Tomkeieff, 1961; Macgregor, 1965; MacDonald and Herriot, 1983; McKerrow and Atkins, 1989) and in the field exercise manual of Nicholas (2000). The site lies adjacent to the Corrie Foreshore GCR site, described in the *British Upper Carboniferous Stratigraphy* GCR volume by Cleal and Thomas (1996), and the Corrie Shore to Brodick GCR site, described in the *Permian and Triassic Red Beds and the Penarth Group of Great Britain* GCR volume by Benton *et al.* (2002).

Description

A simplified log of the succession is presented in Figure 2.38. At the base of the section, Lower Carboniferous strata rest on Upper Old Red Sandstone rocks of the Stratheden Group. Several metres of red sandstones, siltstones and mudstones, arranged in fining-upward cycles, can be seen capped by a thick conglomerate (7 m), which is taken as the basal bed of the Kinnesswood Formation (Inverclyde Group, Lower Carboniferous) (McKerrow and Atkins, 1989). The base of the conglomerate is erosive and in places loaded into the underlying mudstone. The conglomerate, which appears to thicken seawards, is generally coarse, though sandy lenses do occur, and includes clasts of quartzite, vein quartz, schist, green sandstone, red siltstone, calcite and andesitic lava (McKerrow and Atkins, 1989). The top of this conglomerate is distinguished by a prominent calcite cement which defines large ovoid patches incorporating grains and clasts of the conglomerate. Above it is an interbedded and coarsening-upward sequence of red siltstones and light-coloured sandstones in which there are three nodular calcrete developments (Tyrrell, 1928; Macgregor, 1965). Within the upper sandstones, McKerrow and Atkins (1989) recorded a bioturbated shale.

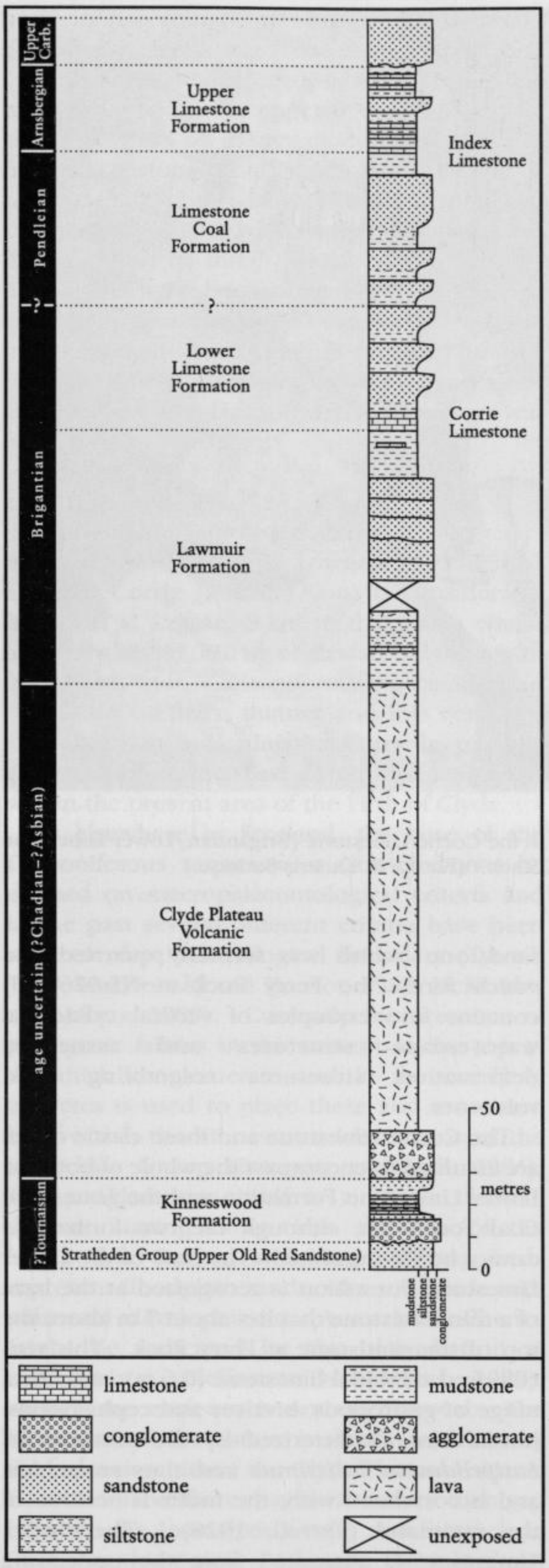


Figure 2.38 Simplified sedimentary log of the Lower Carboniferous succession at the Corrie Shore GCR site.

The Kinnesswood Formation is sharply overlain by beds of the Clyde Plateau Volcanic Formation (Strathclyde Group) which has at its base a thick (15 m), coarse agglomerate overlain by basaltic lava (140 m). The agglomerate is matrix-supported and contains large clasts of basaltic lava which are often highly amygdaloidal. Clasts of red sandstone have also been recorded (McKerrow and Atkins, 1989). The lava development has well-marked columnar jointing but it is only towards its top that an internal flow boundary can be distinguished. At this level and at the top of the development the lava is amygdaloidal, brecciated and reddened.

The overlying beds of the Lawmuir Formation (Strathclyde Group) are not so well exposed. At its base are red shales and sandstones with tuffaceous fragments (20 m). Some of these sandstones are bioturbated (McKerrow and Atkins, 1989) and a thin (0.45 m) red limestone has been recorded (Tyrrell, 1928). Above these, a thin (3 m) altered basaltic lava flow makes a prominent ridge on the shore (NS 025 438). The beds immediately overlying the lava are not exposed and there is a gap in the sequence of about 10 m before the appearance of a thick (30 m) unit of bedded sandstones. These sandstones may be massive or cross-bedded and in places there is convolution of the bedding. On some major bedding surfaces there is evidence of plant colonization including stigmarian roots. The beds above the sandstone (15 m) are again poorly exposed, but include red siltstones and mudstones with reduction spots. Macgregor (1965) recorded a fragment of ribbed brachiopod shell from this part of the sequence, and a red crinoidal limestone, which appears to be *in situ*, can be found under the boulders on the foreshore.

The Corrie Limestone (Figure 2.39), which occurs next in the sequence, is taken as the local equivalent of the Hurlet Limestone (Tyrrell, 1928), and its base, which is not currently exposed, thus marks the base of the Lower Limestone Formation (Clackmannan Group). On the shore, only the upper parts of the limestone can be seen in a vertical face on the south side of the small harbour. However, more extensive exposures showing up to 4.3 m of limestone are available inland in old quarries and at the entrances to old underground workings of the limestone. The limestone was recorded as being 7 m thick. A characteristic feature of the limestone is the abundance of

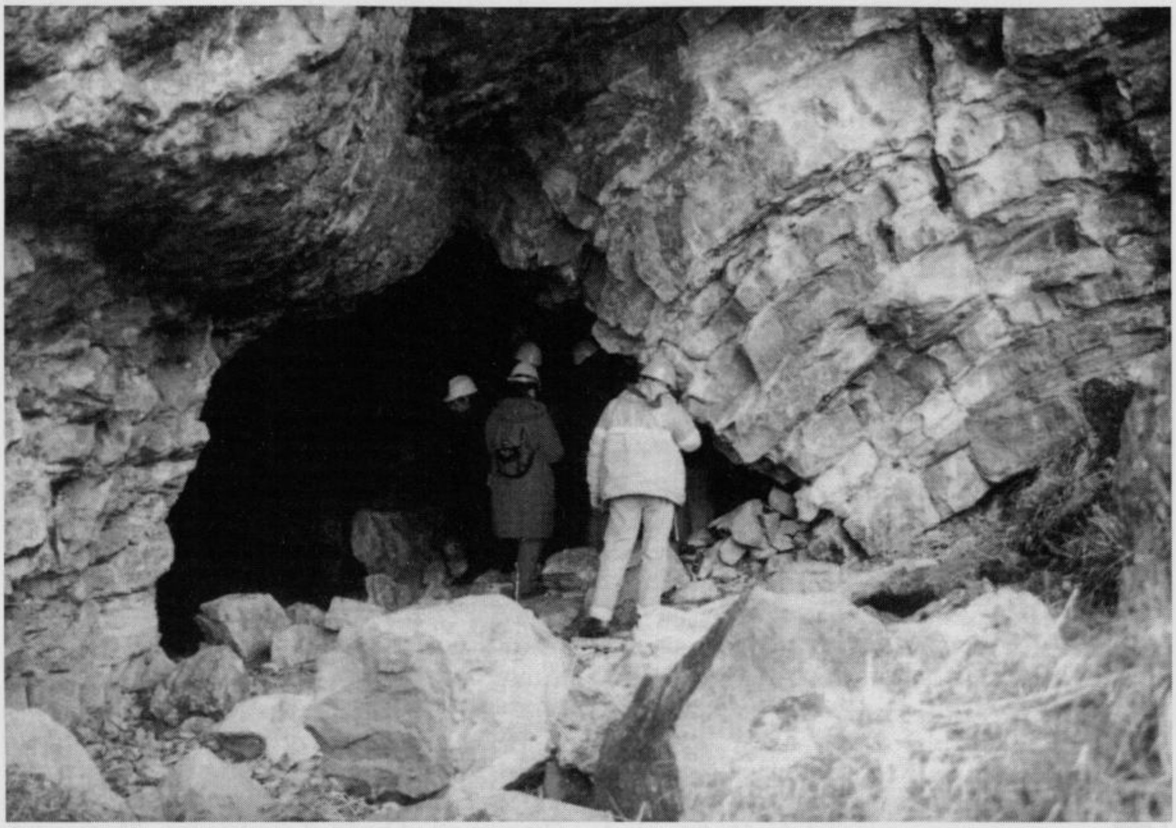


Figure 2.39 Folded beds and entrance to old workings in the Corrie Limestone (Brigantian, Lower Limestone Formation, Clackmannan Group) at the Corrie Shore GCR site. (Photo: R. Kanaris-Sotiriou.)

large gigantoproductid brachiopods, which are often found in a concave-up 'life' position. The limestone in the quarries is overlain by shales (0.5 m) from which a prolific marine fauna has been recorded (Tyrrell, 1928). A thin clay tonstein layer (40 mm) has been recognized from within these shales associated with an earthy layer thought to be a decomposed coal (Huff and Spears, 1989). The shales pass up into siltstones with starved ripples and then into cross-laminated and cross-bedded sandstones. These strata are the first of a series of about six coarsening-upward cycles of shales and siltstone passing up into ripple-laminated or cross-bedded sandstones, which together total about 70–80 m (Tyrrell, 1928; McKerrow and Atkins, 1989). Some of the sandstones contain stigmarian roots and one is a pure white quartz arenite, but no coals have been recorded. Bioturbation is present in some beds (McKerrow and Atkins, 1989) and soft-sediment deformation is common in some of the siltstones and sandstones. The topmost and thickest sandstone (which was formerly quarried and which forms the Ferry Rock at NS 026 435) contains fine examples of vertical cylindrical water-escape structures and associated deformation structures resembling sand volcanoes.

The Corrie Limestone and these clastic cycles are assumed to encompass the whole of both the Lower Limestone Formation and the Limestone Coal Formation, although the two formations cannot be distinguished. The base of the Upper Limestone Formation is recognized at the base of a thin limestone that lies about 7 m above the top of the sandstone at Ferry Rock. This red-coloured crinoidal limestone (0.6 m) contains a range of gastropods, bivalves and cephalopods, but is best characterized by the presence of *Latiproductus latissimus* and thus resembles, and is correlated with, the Index Limestone of the mainland (Tyrrell, 1928). The 'Index Limestone' is separated from the underlying sandstone by reddish shales and sandstones, and within the overlying similar reddish shales and silty sandstones (10 m) a further two thin red limestones occur. The lower (0.3 m) of these contains small gastropods and productoid brachiopods, and the upper is distinguished by an abundance of palaeotaxodont bivalves. A white sandstone (2 m) separates these beds from a similar but less well-exposed sequence (about 7 m) within which two (McKerrow and Atkins, 1989) or three (Tyrrell, 1928) thin red limestones have been recognized. These are erosively overlain by a sandstone with a conglomeratic base, which is the first horizon within the Upper Carboniferous succession (MacDonald and Herriot, 1983; Cleal in Cleal and Thomas, 1996).

Interpretation

The total thickness of Lower Carboniferous rocks at Corrie (about 370 m) is considerably less than at Laggan, 9 km to the north, where there are about 730 m of strata. To the south and south-west, Carboniferous successions in Arran become even thinner and less complete (Tyrrell, 1928), indicating that Corrie lay towards the margin of the East Arran Basin situated within the present area of the Firth of Clyde.

As elsewhere in Scotland, the base of the Carboniferous sequence at Corrie cannot be defined on macropalaeontological criteria and in the past several different criteria have been used to place a lithological boundary (Tyrrell, 1928; MacDonald and Herriot, 1983; McKerrow and Atkins, 1989). Currently the presence of pedogenic fabrics in the cement at the top of the thick conglomerate and in the overlying calcretes is used to place these and associated beds within the Kinnesswood Formation of the Inverclyde Group (Paterson and Hall, 1986). The conglomerate itself is a coarse channel deposit cutting down into the top of the Stratheden Group, and the overlying beds represent floodplain sands, silts and muds with palaeosol developments. A marine influence might be indicated by the bioturbation at one horizon (McKerrow and Atkins, 1989), though the evidence is not unequivocal. The Kinnesswood Formation is sharply overlain by the volcanic units of the Clyde Plateau Volcanic Formation and there may be a marked time gap between the Inverclyde Group and Strathclyde Group at this point. At Laggan there is about 100 m of succession that is not found at Corrie (Tyrrell, 1928; McKerrow and Atkins, 1989).

The basal agglomerate of the Clyde Plateau Volcanic Formation has been interpreted as a lahaar deposit and the dearth of flow boundaries in the overlying lava might indicate either that there was very little time for weathering between eruptions or that the unit is largely the result of a single eruption that was ponded to make an unusually thick unit. Although the top of the lava development is weathered and the basal beds of the Lawmuir Formation do contain volcanic fragments, there is no development at Corrie of the Kirkwood Formation in which beds are almost entirely formed from eroded and weathered volcanic material. The Lawmuir Formation consists largely of floodplain mudrocks, siltstones and sandstones with, towards the middle of the sequence, a group of higher-energy fluvial sandstones. Low down in the sequence a marine influence might be indicated by bioturbation in a mudrock (McKerrow and Atkins, 1989) and by the thin limestone. Marine horizons may also be present in the upper part of the formation. However, the first well-developed and undoubtedly marine horizon is the Corrie Limestone. The correlation of this limestone with the Hurlet Limestone (Tyrrell, 1928) may need to be reconsidered in the light of debate regarding the correlation of the Dockra Limestone of Ayrshire (Wilson, 1979; Whyte, 1981) but, whatever its exact horizon, the Corrie sequence is remarkable in that it lacks any other representatives of marine horizons of the Lower Limestone Formation. Also remarkable is the lack of coals from the levels that approximate to the Limestone Coal Formation. It is possible that coals were once present but have been volatilized by the metamorphic effects of the Northern Granite. Some of the extensive, and possibly secondary, reddening of strata within the sequence may also be linked to pore-water circulation stimulated by the granite intrusion and carrying iron leached from the New Red Sandstones or Old Red Sandstones.

The uppermost groups of thin reddened limestones equate broadly with the Upper Limestone Formation of the mainland, though only the basal limestone can be correlated with any degree of certainty. They do, however, show that marine conditions did occasionally penetrate to the western end of the Midland Valley in late Pendleian and Arnsbergian times.

Conclusions

The Corrie Shore GCR site offers an outstanding and nearly complete outcrop from the Kinnesswood Formation (Tournaisian) through to the Upper Limestone Formation (Arnsbergian). Together with the adjacent Upper Carboniferous GCR site (Corrie Foreshore) described by Cleal and Thomas (1996) it offers arguably the most continuous Carboniferous section in north-west Britain. It also provides invaluable information on Lower Carboniferous palaeogeography and palaeoenvironments at the western end of the Midland Valley.

BRACKEN BAY–LONGHILL POINT, SOUTH AYRSHIRE (NS 277 182–NS 283 187 and NS 292 188–NS 317 194)

Introduction

The long coastal section from Bracken Bay (NS 277 182) to Longhill Point (NS 317 194) reveals a stratigraphically significant section of the Ballagan Formation (Tournaisian Inverclyde Group) and a unique relationship between this and Upper Carboniferous rocks. The outcrop is situated towards the eastern margin of the East Arran Basin but is disrupted by the intrusive complex of the Heads of Ayr Vent (described in detail as part of an igneous site of Carboniferous age described in a companion GCR volume by Stephenson *et al.*, 2003), and by a number of NW–SE-trending dolerite dykes. Descriptions of the site have been published by Eyles *et al.* (1949), and in guides by Bassett (1958) and Whyte (in Bluck, 1973; in Lawson and Weedon, 1992).

Description

At the western end of Bracken Bay the Lower Carboniferous rocks of the Ballagan Formation are faulted against older rocks of the Stratheden Group (Upper Devonian), which are massive, occasionally pebbly, pink and white sandstones and which have yielded the fish scales of *Bothriolepis major*, and a specimen of *Asterolepis*.

The Ballagan Formation consists of alternations of cementstones and mudrocks. The cementstones are thin (less than 0.3 m), hard, argillaceous dolomitic limestones. They are grey in colour but weather to a buff or creamy-brown colour. Some bands may be nodular. The mudrocks, which are a grey to greenish-grey colour, are calcareous and not usually very fissile. Variations in Ca/Mg ratios and insoluble residue content recorded in these beds by Freshney (reported in Belt *et al.*, 1967) were interpreted as the product of carbonate re-distribution from mudrocks into the cementstones by penecontemporaneous downward movement of pore fluids. A few thin beds of fine-grained, micaceous sandstone and thicker and coarser, current-bedded sandstones also occur in the sequence. The thinner sandstones may show ripple marks and desiccation cracks. The latter are also found in the mudrocks. Some of the mudrocks, notably in outcrops 400 m to the east of the Heads of Ayr Vent, show salt pseudomorphs. In this vicinity a mudrock layer contains a fauna of *Lingula*, *Euestheria striata*, *Spirorbis*, small bivalves and fish remains (Bassett, 1958; Whyte in Bluck, 1973; Whyte in Lawson and Weedon, 1992). Bands rich in ostracodes are also found a little lower in the sequence. Within the Heads of Ayr Vent an included mass of cementstone contains abundant bivalves. Indeterminate plant remains have been recorded from the sequence, and in Bracken Bay (NS 283 186) a cementstone horizon about 100 m above the base of the formation has yielded a significant Tournaisian miospore assemblage (Sullivan, 1968; Neves *et al.*, 1973; and see Figure 2.40).

Towards the top of the Ballagan Formation, a unit (15–20 m) of well-bedded tuff or agglomerate forms the eminence on which Greenan Castle is built. The tuff contains many large fragments derived from the Lower Old Red Sandstone (lavas and sedimentary rocks) and from the Ballagan Formation. In addition pieces of fossil wood impregnated with calcite, carbonated peridotite and a large feldspar crystal have also been recorded (Eyles *et al.*, 1949). The tuff rests with apparent conformity on a sandstone and is overlain by tuffaceous shales and cementstones. The characters of the tuff resemble tuffs within the Heads of Ayr Vent and appear to have been erupted from that volcano.

On the shore near Longhill Point the Ballagan Formation is disconformably overlain by strata belonging to the Upper Carboniferous (Namurian) Passage Formation which consist of greenish, plant-bearing sandstones overlain by basalt lavas.

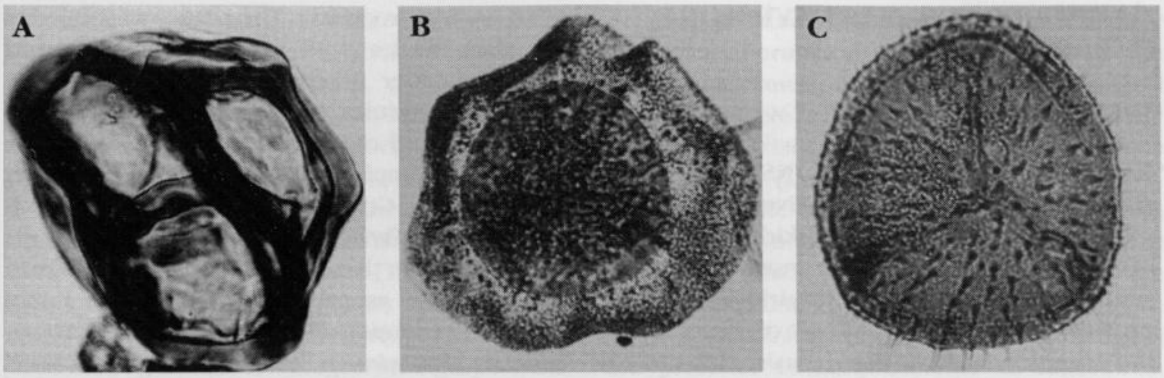


Figure 2.40 Tournaisian miospores from the Ballagan Formation (Inverclyde Group) at Bracken Bay. A – *Knoxisporites pristinus* (× 710); B – *Auroraspora macra* (× 820); C – *Grandispora echinata* (× 810). Reproduced from Sullivan (1968) by kind permission of the Palaeontological Association.

Interpretation

The alternating cementstones and mudrocks of the Ballagan Formation are interpreted as having formed from wide, shallow water bodies in a lagoonal or protected coastal-plain environment (Belt *et al*., 1967). The dolomitic character of the cementstones and the association with desiccation cracks and salt pseudomorphs indicates that the climate was arid, that salinities were at times elevated and hypersaline, and that the water bodies occasionally dried out. The rhythmic character of the sequence may reflect alternating wetter and drier periods. Such environments of high physiological stress are inimical to life and the Ballagan Formation usually contains little or no organic remains. The faunas recorded from the Bracken Bay to Longhill Point section are thus particularly important and the unique presence of the inarticulate brachiopod, *Lingula*, indicates a marginal marine connection.

The miospore flora recorded from a cementstone band is of great stratigraphical importance since it contains spores diagnostic of a Tournaisian (CM Zone) age (Sullivan, 1968; Neves *et al*., 1973; and see Figures 2.2 and 2.40); the first clear record of Tournaisian rocks within the Scottish Carboniferous succession. The fish fauna of the sandstones at the western end of Bracken Bay show that these are of Late Devonian (Fammenian) age (Westoll in House *et al*., 1977; Paterson and Hall, 1986). These floral and faunal records are of crucial value in delimiting the position of the basal Carboniferous boundary within the Midland Valley.

The Ballagan Formation is overlain disconormably by sedimentary rocks and lavas of the Passage Formation (Upper Carboniferous). Thus here the whole of the Clyde Sandstone Formation (Inverclyde Group), the Strathclyde Group sedimentary formations, and the Lower Limestone, Limestone Coal and Upper Limestone formations are absent. The agglomerates of Greenan Castle, which are interbedded within the Ballagan Formation, indicate a volcanic event that pre-dates the eruption of the Clyde Plateau Volcanic Formation (Strathclyde Group).

Conclusions

The sequence at Bracken Bay to Longhill Point offers exceptional sections of the Ballagan Formation (Inverclyde Group) which are critical to the understanding of the early Carboniferous stratigraphy, sedimentology and palaeogeography of the Midland Valley. Key features include the presence of an unusual fauna that has been influential in establishing the depositional environment and setting of the formation, and the occurrence of Tournaisian miospores, which, in association with fish fossils recorded from the underlying Stratheden Group (Fammenian) beds, have helped to delimit the position of the Devonian–Carboniferous boundary in the west of Scotland. The age of interbedded volcanics and the great stratigraphical break between the Tournaisian and Upper Carboniferous (Namurian) rocks are further distinctive features of this locality.

GARPEL WATER, EAST AYRSHIRE (NS 690 255)

Introduction

The Garpel Water GCR site (NS 690 255) is a south bank tributary of the River Ayr which it joins close to the town of Muirkirk, 13 km WNW of Cumnock. Its course runs across the southern limb of the Muirkirk Syncline providing important outcrops of strata within the Muirkirk Basin, a small basin close to the south-west margin of the Midland Valley (Figure 2.1). The discontinuous exposures show key horizons of the Lower Limestone Formation (Brigantian) and the Upper Limestone Formation (Arnsbergian), which also have features of wider significance within the Midland Valley as a whole. The geology of the Muirkirk Basin and of the Garpel Water outcrops has been described by Eyles *et al.* (1930) and Davies (1972).

Description

In the Garpel Water, the exposures of the Lower Limestone Formation provide sections of three marine horizons. The oldest beds exposed are partial exposures of the Hawthorn Limestone, which is the lowest limestone in the Lower Limestone Formation. These are beds of shelly limestone and calcareous shales (1.7 m). About 8 m of strata separate these beds from the higher part of the Hawthorn Limestone, which contains solitary corals and large gigantoproductid brachiopods set in a nodular white-weathering limestone with reddish-weathering sideritic patches on its upper surface. The limestone has been invaded by rootlets from the overlying bed of mudstone, which, in addition to rootlets, contains sphaerosiderite and has a polygonal pattern of sandstone-filled shrinkage cracks. Above the mudstone there is an alternating series of hard and soft sandstones with rootlets overlain by dark carbonaceous shales with carbonate nodules.

The Garpel Water also proves an excellent section of the next marine band in the local sequence, the Muirkirk Wee Limestone, which is 0.7 m thick and rich in gigantoproductids. It rests on dark shales and is overlain by dark, unfossiliferous shales with large ironstone nodules (0.7 m) capped by an ironstone band with rootlets (0.15 m) and a grey seatearth (0.8 m) with rootlets. The seatearth is overlain by dark shales with plant fragments, which become siltier at the top with siderite and carbonate nodules. Overlying these are 7.3 m of limestone and calcareous shales, which provide a nearly complete section of the McDonald Limestones. Corals, trilobites, gastropods and the bivalve *Pernopecten sowerbii* have been recorded from these beds (Davies, 1972) as well as a diverse range of brachiopods including *Avonia youngiana*, *Echinoconchus*, *Latiproductus latissimus* and other productoids, chonetoids, *Schizophoria*, *Composita* and orthotetoids. Snook (1999) has made a detailed study of the faunas and facies of these beds and of the Muirkirk Wee Limestone.

Exposures of the Upper Limestone Formation include outcrops of four marine horizons, towards the middle of the formation, together with associated strata. In ascending order, these are the Birchlaw Limestone, Tibbie Pagan's Limestone, the Orchard Beds and the Blue Tour Limestone. An incomplete section of the Birchlaw Limestone shows a sandy limestone (1.8 m) with brachiopods (*Pleuropugnoides* and *Schellwienella rotundata*) and bivalves. The Tibbie Pagan's Limestone lies about 60 m higher in the formation at the eponymous locality of Tibbie Pagan's Bridge, the only exposure of this unit on the southern limb of the Muirkirk Syncline. Here, 1.5 m of shelly limestone is overlain by fossiliferous calcareous mudstones and limestone bands (1.8 m). Fenestellids, bivalves including *Aviculopecten*, *Nuculopsis gibbosa* and *Phestia attenuata*, gastropods and brachiopods such as *Eomarginifera*, *Latiproductus*, *Pleuropugnoides* and orthotetoids have been recorded from this locality (Davies, 1972). Above this, the Orchard Beds (*c.* 11 m) are a series of calcareous shales and siltstones with thin limestone bands. The Garpel Water outcrop is the best exposure of this horizon in the Muirkirk Basin, and a diverse fauna of small solitary corals, bryozoans, brachiopods, bivalves, gastropods, scaphopods, cephalopods, trilobites and crinoid remains occurs within it (Davies, 1972). The Blue Tour Limestone lies about 25 m higher in the section, and up to 6 m of limestone and limestone with calcareous shale partings can be seen (Davies, 1972). As noted by Davies (1972), a thicker section was recorded in the past (Eyles *et al.*, 1930) when the limestone was also seen to rest on a coal seam (Davies, 1972). Muir and Hardie

(1956) have provided a brief petrographical description and chemical analysis of this limestone. Its fauna includes *Clisiophyllum*, *Composita*, *'Dielasma'*, *Pugilis*, *Eomarginifera*, *Latiproductus* and other productoids, trilobites and crinoid columnals (Davies, 1972), and Graham (1988) has recorded the problematical bivalve *Placunopsis*? *propediscus* from the horizon. In addition, Currie (1954) recorded the goniatites *Anthracoceras paucilobum* and *Cluthoceras*, and Wright (1936, 1939, 1950–1960) described *Allagecrinus garpelensis* from the Blue Tour Limestone at this locality. Two other crinoid species, *Platycrinites muirkirkensis* and *Woodocrinus whytei*, have also been described from the Garpel Water (Wright, 1950–1960). Although the exact horizons are not given, the former is from the Upper Limestone Formation and the latter from the Lower Limestone Formation. Wright (1950–1960) also recorded *Ureocrinus bockshii*, *Platycrinites* ?*crassiconicus* and *Platycrinites* ?*spiniger* though their source horizons are also uncertain.

Interpretation

The Hawthorn Limestone is the local name for the Hurlet Limestone (Davies, 1972; Whyte, 1981; and see Figure 2.2) and the fauna recorded is typical of this horizon in the Muirkirk Syncline. The bleached and nodular top to the Hawthorn Limestone, which is also typical in this area (Davies, 1972), indicates the presence of a disconformity accompanied by penecontemporaneous weathering of the limestone. The regional significance of this break has been discussed by Whyte (1981). The rapid transition from limestone to fireclay above the Muirkirk Wee Limestone suggests that uplift also occurred locally at this horizon. The McDonald Limestones may include up to four limestone horizons, which are thought to equate to the four limestones of the Hosie Limestones of the Central Coalfield Basin (Davies, 1972; Whyte, 1981). In the Garpel Water, Snook (1999) tentatively identified limestone bands equivalent to the two lower units of the Hosie Limestones, the Main Hosie Limestone and Mid Hosie Limestone. He also indicated that the position of the Second Hosie Limestone might lie within a carbonate-rich series of shales and limestone bands (Snook, 1999). The equivalent of the Top Hosie Limestone, whose top marks the top of the Lower Limestone Formation, is not exposed in the Garpel Water.

The Birchlaw Limestone, in the Upper Limestone Formation, is correlated with the Shell Band Limestone of the Douglas Coalfield (Lumsden 1967a; Davies, 1972), but the equivalent horizon in the Central Coalfield Basin is less certain (Lumsden, 1967a; Wilson, 1967). In the past, the Birchlaw Limestone appears to have been mis-correlated with the Index Limestone, which is the basal limestone of the Upper Limestone Formation (Eyles *et al.*, 1930). A characteristic feature of the Index Limestone is the presence of *Latiproductus* cf. *latissimus*, but, as is well shown in the Garpel Water, it is not confined to this horizon (Davies, 1972). The Tibbie Pagan's Limestone, Orchard Beds and Blue Tour Limestone are correlated respectively with the Lyoncross Limestone, the Orchard Limestone and the Calmy Limestone of the Central Coalfield (Eyles *et al.*, 1930; Wilson, 1967; Davies, 1972; and see Figure 2.5). An interesting feature of the Orchard Beds (Orchard Limestone) is that *Edmondia punctatella* is found at their base. In other areas this species is more usually found in a band at the base of the Calmy Limestone (Eyles *et al.*, 1930; Wilson, 1967; Davies, 1972) but in the Muirkirk Basin it has only been found at the earlier Orchard Beds horizon (Eyles *et al.*, 1930; Davies, 1972). The goniatites found in the Blue Tour Limestone are indicative of the E_2 Zone (Currie, 1954). The crinoid fauna recorded by Wright (1950–1960) is particularly significant as this is the only locality in the Upper Limestone Formation of the Midland Valley from which complete dorsal cups have been recorded. The Garpel Water is the type locality for three of the six species listed from it, namely *Woodocrinus whytei*, *Allagecrinus garpelensis* and *Platycrinites muirkirkensis* (Wright, 1950–1960). A paratype of the brachiopod *Leptagonia smithi* comes from the Orchard Beds (Brand, 1972) and the holotype of *Placunopsis*? *propediscus* comes from the Blue Tour Limestone (Graham, 1988).

Conclusions

The natural exposures in the Garpel Water GCR site provide highly important representative sections of the Lower Limestone Formation (Brigantian) and the Upper Limestone Formation (Arnsbergian) within the Muirkirk Basin. The limestones contain rich faunas, which are of taxonomic and biostratigraphical importance and of considerable use in correlation with other parts of the Midland Valley and in palaeogeographical reconstructions. The sequence also shows evidence of a significant disconformity within the Lower Limestone Formation, and contains rich crinoid faunas, which are unique within the Upper Limestone Formation.

KENNOX WATER, SOUTH LANARKSHIRE (NS 777 247–NS 792 259)

Introduction

Kennox Water is a tributary of the Douglas Water about 7 km SSW of Douglas and at the southern end of the Douglas Coalfield. In a series of natural exposures along its course (NS 777 247–NS 792 259) it provides the most complete Lower Carboniferous section within the Douglas Coalfield and a section of invaluable regional importance to the understanding of Lower Carboniferous stratigraphy and palaeogeography of the south-western part of the Midland Valley area. The oldest members of the succession belong to the Inverclyde Group (Tournaisian), and the youngest beds are close to the top of the Upper Limestone Formation of the Clackmannan Group (Arnsbergian). At its base, and within the succession, there are a number of stratigraphically significant unconformities. Full details of the sequence have been given by Lumsden (1964, 1967a,b) who also provides lucid reviews of previous work on the area. Lumsden (1971) has also written a brief excursion guide to the section.

Description

The outcrops on the Kennox Water show a sequence of strata belonging to the Inverclyde Group (Tournaisian) unconformably overlain by beds of the Lawmuir Formation (Strathclyde Group) and the Lower Limestone, Limestone Coal and Upper Limestone formations (Clackmannan Group, Brigantian to Arnsbergian). The general succession is illustrated in Figure 2.41. The beds assigned to the Inverclyde Group rest with a marked angular discordance on Lower Devonian rocks of the Lower Old Red Sandstone. At the base of the Inverclyde Group, which has a thickness of

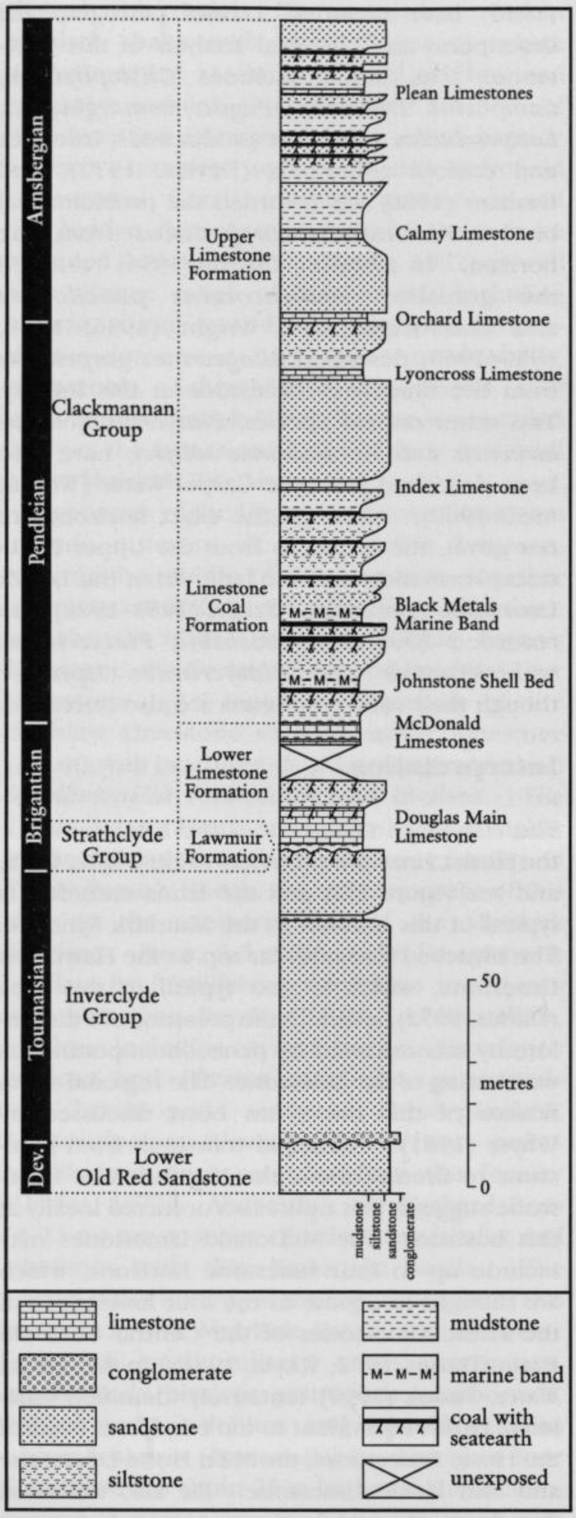


Figure 2.41 Generalized sedimentary log of the Lower Carboniferous succession in the Kennox Water area. After Lumsden (1964, 1967a,b, 1971).

75 m, there is a conglomerate and the rest of the sequence is made up of massive, medium-grained sandstones with bands of conglomerate and thin red or green mudrocks. Prior to Lumsden's work (1967a), a conglomeratic horizon about 13 m below the top of the Inverclyde Group was taken as marking the base of the Carboniferous sequence and the beds below were assigned to the Old Red Sandstone.

The Inverclyde Group is capped by a pale-coloured seatearth, which is overlain by calcareous mudstones (1 m) and a limestone. The limestone, the Douglas Main Limestone, is correlated with the Hurlet Limestone (Lumsden, 1967a; Whyte, 1981) and thus its base defines the base of the Lower Limestone Formation (Figure 2.2). Its basal shales and the seatearth thus represent a very thin development of the Lawmuir Formation (Brigantian). The Douglas Main Limestone is 10 m thick and consists of beds of limestone with shale partings and thicker bands of calcareous mudstone. It contains corals, echinoderm debris and brachiopods including gigantoproductids. An assemblage of *Antiquatonia* spp., *Avonia youngiana* and *Krotovia spinulosa*, which is found in the limestone both at Kennox Water and elsewhere, is, within the Douglas Basin, unique to this horizon (Lumsden, 1967a). The limestone is overlain by sandstone (7.5 m) with thin, rooty siltstones and mudstones in the middle and a seatearth and thin coal at the top. There is also a seatearth at the base and rootlets penetrate down into the top of the limestone, which is bleached. Reworked clasts from the limestone occur in the basal parts of the fireclay and there is also in-situ brecciation in the top of the limestone.

The middle parts (about 8.5 m) of the Lower Limestone Formation, including the Douglas Wee Limestone position and the lower part of the McDonald Limestones succession, are not exposed in the Kennox Water, but there are exposures of the upper two limestones of the McDonald Limestones. The lower limestone is 1.0 m thick and separated from the upper limestone (0.4 m), which has a red-weathering top, by 1.0 m of calcareous shales. The fauna of these beds includes corals, crinoids, bryozoans, trilobites, bivalves (including *Wilkingia* and *Pernopecten sowerbii*) and a wide variety of brachiopods (Lumsden, 1967a). The McDonald Limestones are correlated with the Hosie Limestones of the Central Coalfield (Lumsden, 1967a; Whyte, 1981) and the top of the highest limestone marks the top of the Lower Limestone Formation.

The Kennox Water provides excellent representative sections of the Limestone Coal Formation (Pendleian), which is about 60 m thick in this area (Lumsden, 1964). The beds are arranged in cycles with variable developments of the following sequence: coal, overlain successively by mudstone, siltstone and sandstone capped by the seatearth of the next coal. In the Kennox Water there is an excellent exposure of one of the principal marine bands of the formation, the Johnstone Shell Bed (Figure 2.41). This is a 2 m-thick, highly fossiliferous, calcareous mudstone containing *Edmondia*, *Limipecten*, *Lingula squamiformis* and brachiopods including productoids, spiriferoids and rhynchonellids (Lumsden, 1964). The Shell Bed rests on a thin coal, the McDonald Coal (0.45 m), and is separated from the top of the McDonald Limestones by about 10 m of rooty sandstones and siltstones with clayband ironstones. Above the Johnstone Shell Bed, clayband ironstones and mudstones (2 m) containing *Lingula* pass up into rooty sandstones, siltstones with ironstone nodules and seatearths with rootlets (14 m), which also contain, in the upper parts, two coal seams. These are the Six Foot Coal and the Thirty Inch Coal, both of which are developed as two leaves separated by seatearths. Above this, a mudstone marks the position of the Black Metals Marine Band, though fossils have not been found in the outcrops in the Kennox Water. There is a gap of about 10 m above this mudstone. In the uppermost 20 m of the Limestone Coal Formation a number of coal seams can be recognized separated by mudstones, sandstones and seatearths. The lowest of these coals is the Nine Foot Coal (2.7 m), which is in bands with dirt partings, and above this is the Seven Foot Coal (1.9 m), which is in two leaves of coal with thin dirt partings separated by a mudstone and seatearth. The highest coal, the Ell Coal, is 0.5 m thick and lies 5–6 m below the top of the formation.

The outcrops of the Upper Limestone Formation (Pendleian–Arnsbergian) are not complete but supply sections typical of the formation as well as exposures of some of its key horizons. At the base the Index Limestone is well displayed and consists of 2.4 m of limestone with shale bands resting directly on a thin coal. The fauna includes *Latiproductus* cf. *latissimus*. The limestone is directly overlain by at least 12 m of medium- to coarse-grained, cross-bedded sandstone. The sequence between the sandstone and the Calmy Limestone is poorly exposed. A small outcrop of the Calmy Limestone does occur in the Kennox Water and its marine fauna includes *Latiproductus* cf. *latissimus*, *Spirifer* and *Rugosochonetes*. The Calmy Limestone is 1.5 m thick, including a calcareous mudstone parting. At the base is a band with the anomalodesmatid bivalve *Edmondia punctatella*. Corals, bryozoans, crinoids, *Composita*, *Echinoconchus*, and other productoids, orthotetoids, *Dentalium*, *Edmondia*, *Sanguinolites* and trilobite fragments are among the faunal elements found in the limestone and shales. The limestone is overlain by siltstones (5 m), which pass up into alternating sandstones and siltstones (10 m). Above these, broken exposures show at least 20 m of thin coals, mudstones, siltstones, thinly bedded sandstones and rooty seatearths. Ironstone bands and nodules are common, and a band containing the non-marine bivalve *Curvirimula* and three marine bands known as the 'Plean Limestones' have also been recognized. The fauna of these includes crinoids, *Lingula* spp., productoids and other brachiopods, bivalves including *Schizodus* and *Edmondia*, orthoconic cephalopods and gastropods. The thickest coal is about 1 m thick.

At Kennox Water these are the highest beds of the Upper Limestone Formation exposed and they are faulted against the Lower Coal Measures. However, it is, thought that the highest beds of the Upper Limestone Formation, including the Castlecary Limestone, are missing locally and that the formation is unconformably overlain by the Lower Coal Measures (Lumsden, 1967b).

Interpretation

The basal beds of the Inverclyde Group have been deposited from a fluvial regime in a semi-arid climate and have filled in hollows in an irregular landscape following a period of uplift and erosion (Lumsden, 1967a, 1971). They have been compared to the calcrete-bearing beds of the Kinnesswood Formation (Inverclyde Group) elsewhere, but calcretes are lacking in the Kennox Water outcrops. In view of the uncertainty as to their age, and because of the proximity of sediment sources in the Southern Uplands, the beds in the Kennox Water could be the lateral equivalent of other parts of the Inverclyde Group. Thus assignment of the sequence to a definite formation could be premature.

The Inverclyde Group is overlain by a very thin development of the uppermost parts of the Strathclyde Group. The two groups are separated from each other by a major unconformity in which most of the Strathclyde Group and possibly the upper parts of the Inverclyde Group are missing. This unconformity must also have had a considerable relief as earlier beds (over 70 m) of the Lawmuir Formation, including three marine bands, occur in other parts of the Douglas Basin. The fireclay at the boundary between the Inverclyde Group and Strathclyde Group reflects a climatic change to more humid seasonally wet conditions.

Although not completely exposed, the Lower Limestone Formation is thinner in the Kennox Water than in the northern part of the Douglas Coalfield (Lumsden, 1967a) and thinner than the formation as developed in the Central Coalfield (Goodlet, 1957). It shows a smaller proportion of argillaceous strata and an increased relative proportion of limestone and sandstone. The increased sandstone content may reflect proximity to sediment sources in the Southern Uplands, but lithological ratios may be affected by the presence of disconformities such as the one above the Douglas Main Limestone (Whyte, 1981). The clastics represent deltaic infill of the basin, which suffered intermittent uplift while the marine beds were deposited in a shallow-shelf environment. The faunas of the McDonald Limestones were included by Snook (1999) in his multivariate study of facies and faunas in the Hosie Limestones. The contention that the gigantoproductids of the Douglas Main Limestone could be differentiated from those of a lower horizon has not been supported by Wilson (in Lumsden, 1967a), who also found no pattern of variation in the colonial coral *Siphonodendron*.

The Limestone Coal Formation shows a marked change in facies and a dominance of delta-top environments. The formation of coals indicates a humid climate with high water tables. Marine conditions are less commonly developed and although the position of the two principal marine bands of the Limestone Coal Formation can be recognized, only one contains marine fossils. The presence of these bands is an aid in correlating coal seams both in the Douglas Coalfield and in other areas of the Midland Valley (Lumsden, 1964).

A reversion to a more Yoredale type of cyclicity is shown in the Upper Limestone Formation, with open marine shelf sequences alternating with deltaic and delta-top beds. In the Kennox area, sandstones can again be thick and prominent, as above the Index Limestone. The variable sequences above the Calmy Limestone suggest unstable oscillating conditions on a delta top with occasional marine influxes (Lumsden, 1971).

Conclusions

The Kennox Water section is highly instructive in showing important relationships between Inverclyde Group (Tournaisian), Strathclyde Group (Brigantian) and Clackmannan Group (Brigantian–Arnsbergian) successions. This extremely significant section represents the infill of a minor sedimentary basin (the Douglas Basin, see Figure 2.1) in the south-west of the Midland Valley. It is, however, also highly significant regionally for its representation of Lower Limestone Formation, Limestone Coal Formation and Upper Limestone Formation sequences, facies and faunas. The basal disconformity is unusual and both it and other disconformities in the succession yield invaluable evidence of phases of tectonic instability within the Douglas Basin and in the Midland Valley as a whole.