Chapter 2 Dinantian volcanic rocks of the Midland Valley of Scotland and adjacent areas

Introduction

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In contrast to the Northumberland, Solway and Tweed basins, where local volcanism commenced during Tournaisian time (see Chapter 3), volcanism did not start in the Midland Valley of Scotland until earliest Visean time. However, the resulting eruptions rapidly built up vast lava fields, which are by far the thickest and most extensive in the whole Carboniferous-Permian Igneous Province of northern Britain and probably constitute over 90% by volume of its eruptive products. Tomkeieff (1937) estimated that almost 6000 km^3 of magma was erupted during Dinantian times and some of the preserved volcanic successions are up to 1000 m thick (Paterson *et al.,* 1990). The most extensive lava fields are those of the Clyde Plateau, which dominate the landscape of the western Midland Valley to the north, west and south of Glasgow (Geikie, 1897). Possible outliers of these fields occur just across the Highland Boundary Fault in southern Kintyre and on Ben Bowie, near Helensburgh. In the eastern Midland Valley, the largest lava field is centred upon the Garleton Hills of East Lothian, and small but prominent outcrops occur within the city of Edinburgh. Later in Visean time, volcanic activity became centred upon the Burntisland area of Fife and the Bathgate Hills of West Lothian. The strati-graphical range of each succession of Dinantian volcanic rocks is shown in (Figure 2.1) and their distribution in and around the Midland Valley is shown in (Figure 2.2).

The early Visean volcanic successions are dominated by lavas, although considerable thicknesses of pyroclastic rocks and volcani-clastic sedimentary rocks occur locally. Uniquely within the Carboniferous-Permian Igneous Province of northern Britain, they are characterized by a wide range of compositions and, although most successions are dominated by transitional to mildly alkaline basalts, hawaiites and mugearites, many include trachytic rocks and some have rhyolites. Late Visean volcanism, in contrast, was exclusively basic in character.

The volcanism appears to have started approximately synchronously across much of the Midland Valley, around the Tournaisian–Visean boundary. In the east, the earliest volcanic rocks rest conformably upon the Ballagan Formation, and CM to PU zone miospores and plant remains have been found just below and within them (Davies, 1974; Bateman and Scott, 1990; Scott, 1990). In the west, the Clyde Plateau Volcanic Formation rests with regional unconformity on strata that range from the Stratheden Group (Upper Devonian) to the Clyde Sandstone Formation, which overlies the Ballagan Formation at the top of the Inverclyde Group (Paterson and Hall, 1986). However, in the south-west of the Kilpatrick Hills, thin sandstones occur in the lowest part of the Clyde Plateau Volcanic Formation, and below the northern escarpment of the Touch and Gargunnock hills tuffs occur in the top of the Clyde Sandstone Formation. In these areas, the boundary is clearly transitional and the volcanic succession is conformable with the Clyde Sandstone Formation.

The early Visean volcanic rocks are overlain more-or-less conformably in the east by strata of the Gullane Formation, which have yielded Asbian TC zone miospores (Neves *et al.,* 1973). In the west, the Clyde Plateau lavas built up a considerable topographical feature that was denuded to produce volcaniclastic detritus, which overlies the lavas wherever the top of the sequence has been preserved. This highly diachronous Kirkwood Formation was then gradually overlapped by a range of late Visean strata, the oldest of which are from the lower parts of the Lawmuir Formation, of possible late Asbian age. Hence the early Visean activity is quite well constrained to the PU and TC miospore zones (Chadian to early Asbian). The major later Visean volcanic centre in the Burntisland area of Fife occurs within the Sandy Craig and Pathhead formations, which are well constrained elsewhere by miospore data to the Asbian–Brigantian interval (Brindley and Spinner, 1987, 1989; Browne *et al.,* 1996). In the Bathgate Hills, volcanism commenced in latest Asbian time and continued well into Namurian time.

Radiometric ages obtained from Dinantian volcanic rocks of the Midland Valley are confusing, mainly because of a scarcity of suitable material, for which only K-Ar whole-rock determinations have been published. De Souza (1982), summarizing his earlier work, suggested that the bulk of the Clyde Plateau Volcanic Formation lavas were erupted

between 335 Ma and 325 Ma and the De Souza (1979) data, adjusted for new constants, gave an age of *c.* 326 Ma for the Kinghorn lavas and 326–316 Ma for the Bathgate Hills lavas. These dates fit well with the biostratigraphical data and the Gradstein and Ogg (1996) timescale. The East Lothian phonolitic intrusions of Traprain Law and North Berwick Law gave dates of *c.* 328 Ma, suggesting that they were contemporaneous with the Visean activity. However, dates for the Arthur's Seat and East Lothian lavas (Fitch *et al.,* 1970; De Souza, 1974), adjusted for new constants, ranged from 355 Ma to 345 Ma, suggesting an earlier, Tournaisian episode, which is inconsistent with the biostratigraphy. Recently obtained, more precise Ar-Ar dates from separated minerals have confirmed the age of the Clyde Plateau lavas at 335 Ma to 329 Ma and have also suggested that the East Lothian lavas may be slightly older (up to 342 Ma), though this latter date is close to the Tournaisian–Visean boundary and hence consistent with the biostratigraphy (A.A. Monaghan and M.S. Pringle, pers. comm., 2002).

Structural control

Structural controls of volcanism are inferred from NE- to ENE-trending lineaments that were particularly well developed during Dinantian times and are assumed to reflect Caledonian trends in the underlying basement. The lineaments are defined by elongate outcrops of proximal volcanic rocks, chains of plugs and/or volcanic necks and local linear dyke-swarms, all suggesting that the ascent of magma was probably controlled by planes of weakness in the deep crust that gave rise to faulting at higher levels.

The graben of the Midland Valley was clearly a major control, yet there is no evidence of volcanism directly associated with the Highland Boundary Fault. The most north-westerly extrusive centres on this side of the Midland Valley are concentrated on the NNW side of the main volcanic outcrops, within a 2–3 km-wide zone that extends ENE for some 27 km, from Dumbarton towards Stirling (Figure 2.3). This lineament has become known as the 'Dumbarton–Fintry Line' (Whyte and MacDonald, 1974; Craig and Hall, 1975). It is marked by numerous intrusions (many of them forming prominent landmarks such as Dumbarton Rock, Dumgoyne and Dunmore), pipes occupied by fragmentary materials, and proximal bedded pyroclastic rocks that probably represent degraded tuff-cones. These features are particularly well seen in the Campsie Fells GCR site. A concentration of dykes along a similar trend to the south-west suggests that the lineament may continue through the Renfrewshire Hills to south Bute. The north-eastern end of the lineament comprises the North Campsie Linear Vent System, and two slightly younger linear vent systems form separate *en échelon* lines within the Campsie lava block to the southeast (Forsyth *et al.,* 1996). On the south side of the Campsie Block, the South Campsie Linear Vent System forms a 15 km-long lineament close to the Campsie Fault (Craig and Hall, 1975; Forsyth *et al.,* 1996).

Other lines of necks and plugs in the northern Clyde Plateau outcrop are aligned WNW–ESE to north-west–south-east and may reflect less extensive conjugate Caledonian fractures at depth. Notable examples occur at each end of the Kilpatrick Hills, at Dumbarton and Strath Blane, where their coalescing tephra cones may have acted as local barriers between adjacent lava fields during the earlier phases of volcanism (Hall *et al.,* 1998).

Other WSW- to nearly W–E-trending faults throughout the Midland Valley that may have been utilized by rising magmas, also probably formed active escarpments controlling local accumulations of lava. Consequently they are commonly marked by significant changes in thickness of the volcanic piles. These faults include the Paisley Ruck, and the Dusk Water and Inchgotrick faults in Ayrshire (McLean, 1966; Hall, 1974; Rollin in Monro, 1999), as well as the Campsie and Ochil faults (Rippon *et al.,* 1996) (Figure 2.2). The unconformity beneath the lavas in the west has been attributed to a localized mid-Dinantian east–west compressional event (Paterson *et al.,* 1990). However, a close association between the maximum excision of strata and the thickest developments of volcanic rocks led Monro (1982) and Forsyth *et al.* (1996)to suggest that it was due, at least in part, to magmatic updoming in advance of the Visean eruptions.

At the south-eastern limit of the Midland Valley, the north-eastern extrapolation of the main Southern Upland Fault, together with NE-trending splays to the south-east, in particular the Dunbar–Gifford Fault, are thought to pass beneath Carboniferous strata (Max, 1976; Floyd, 1994) and to have controlled the rise of magma throughout much of the Carboniferous Period (Upton, 1982).

Palaeogeography and styles of eruption

In the eastern Midland Valley, the earliest volcanic rocks seem to rest conformably on the mudstones, siltstones and dolomitic limestones of the Ballagan Formation. Therefore, they were probably erupted onto flat low-lying coastal plains and deltas, with semi-marine lagoons and sabkhas. The explosive interaction of magma with surface and ground water resulted initially in phreatomagmatic eruptions, evidence for which is well seen in East Lothian, particularly in the North Berwick Coast GCR site. Abundant small vent structures and bedded pyroclastic rocks with base-surge and ash-fall characteristics are interbedded with the sedimentary succession, suggesting the development of shallow tuff-rings, probably less than 1 km in diameter. Lacustrine sedimentary rocks in some of the vents suggest the presence of crater lakes (maars) and some preserve remnants of early terrestrial tropical vegetation.

Farther inland, generally to the west, were semi-arid floodplains, with outwash fans and playa lakes. This transition from coastal plain to the entirely terrestrial, fluvial environment, typified by the Clyde Sandstone Formation and indicating regional uplift, was probably diachronous across the Midland Valley and broadly coincided with the onset of volcanism. The plains may have been divided initially by NE-trending ridges and escarpments formed from pre-Carboniferous rocks but, with a rise in magma productivity, rapidly accumulating lava fields began to form major landscape features. These topographic highs dominated the late Visean palaeogeography and also had a long-lasting influence on subsequent basin development. In such areas, eruptions were almost entirely subaerial and lavas were usually of as type, though rare pahoehoe features have been reported. Flow surfaces are rarely preserved and thick red-brown boles occur on the top of most flows, resulting from the development of tropical or sub-tropical lateritic soils, indicative of significant interludes of quiescence between eruptions. Basic to mugearitic lavas, typically between 5 m and 30 m thick, were erupted through relatively small shield volcanoes. Together with cinder cones of coarse pyroclastic rocks, these commonly coalesced along NE-trending lineaments, now marked by upstanding plugs and volcanic necks. This style of eruption is represented by the Campsie Fells GCR site.

The absence of volcanic necks and proximal pyroclastic rocks from some areas suggests eruption from fissure volcanoes. The Touch, Fintry and Gargunnock Hills GCR site represents one such area, and the lateral continuity of some flows for over 6 km in the escarpment of the Gargunnock Hills has been cited as further evidence of fissure eruptions (Read in Francis *et al.,* 1970). Regional dyke-swarms that may have acted as feeders to the fissure eruptions are not obvious in most lava successions. However, there is a marked concentration of ENE- to NE-trending dykes up to 12 m wide along a southwestern continuation of the Dumbarton–Fintry volcanotectonic line, which can be traced beneath the thickest part of the Renfrewshire Hills succession (Paterson *et al.,* 1990), across Great Cumbrae (Tyrrell, 1917a) and into southern Bute (Smellie, 1916). Outwith the major lava fields, individual volcanoes such as Arthur's Seat and the Heads of Ayr were possibly up to 5 km in diameter and rose to heights of about 1000 m above the plain (Whyte, 1963b; Black, 1966).

More evolved lava compositions are common locally in the Dinantian lava fields, and the abundance of trachytic extrusive rocks in the southern crop of the Clyde Plateau Volcanic Formation between Greenock and Strathaven implies that higher stratovolcanoes may have developed in this region (MacPherson *et al.,* 2001). The best-documented example is the 8 km-wide Misty Law Trachytic Centre in the Renfrewshire Hills, which comprises trachytic pyroclastic rocks, massive lavas of trachyte and rhyolite, and trachytic plugs and necks (Johnstone, 1965; Stephenson in Paterson *et al.,* 1990). Trachyte lavas are also abundant in the upper part of the Garleton Hills Volcanic Formation and the Garleton Hills GCR site has been selected to represent this style of volcanism. They are also present in the upper part of the Machrihanish succession (see Machrihanish Coast and South Kintyre GCR site report). Rhyolites occur locally in the upper part of the succession in the western Campsie Fells and near the base of the sequence in the Cleish Hills (Geikie, 1900). Flow banding in many of these evolved lavas indicates viscous flow; they probably never extended more than a few kilometres from their source and may even have formed steep-sided lava domes (e.g. the trachyte of Skerry Fell Fad, near Machrihanish and the rhyolite at Swinlees in the southern Renfrewshire Hills).

Calderas may have developed over some of the principal salic centres and the thick trachyte lavas forming the Garleton Hills of East Lothian may have been ponded in a caldera (B.G.J. Upton, pers. comm., 2001). However, the best-documented evidence occurs in the Waterhead Volcanic Complex of the Campsie Fells (Craig, 1980; Forsyth *et al.,* 1996). Here, a large multiple neck and several smaller necks, plugged by a wide variety of rock-types, occur within an oval ring-fault 2 km by 2.5 km. The complex is underlain by a positive gravity anomaly (Cotton, 1968) and the enclosed basic lavas show intense brecciation and hydro-thermal alteration and are intruded by a variety of dykes (MacDonald,

1973). Some of the dykes are felsic, and trachytic pyroclastic rocks in the adjacent tephra cone of Meikle Bin have been attributed to the centre, although there are no felsic lavas preserved.

Despite the abundance of felsic volcanic rocks and the inferred presence of calderas in some areas, there is little evidence for pyroclastic flows, which are typical of such activity elsewhere. Well-bedded, carbonated and haematitized trachytic tuffs near the Weak Law Vent in East Lothian that were originally interpreted as welded ash-flow tuffs (Upton in Sabine and Sutherland, 1982), are now considered to be ash-fall material (see North Berwick Coast GCR site report). Welded trachytic lapilli-tuffs near Eaglesham have also been interpreted as ash fall (MacPherson and Phillips, 1998).

In the West Lothian oil-shale field, the land surface remained close to sea level during Dinantian times and similar conditions prevailed during most of Silesian time throughout the eastern Midland Valley. Relatively small basaltic volcanoes erupted onto coastal plains with lagoons and into shallow seas, locally building volcanic islands, fringed by reefs that were periodically eroded and submerged. Initial eruptions were explosive (phreatomagmatic), leading to widespread pyroclastic deposits, but later eruptions in any one area were dominantly of lavas. Pillow lavas and hyaloclastites at Kinghorn testify to local subaqueous eruptions, but most of the lavas were probably subaerial.

The eastern Midland Valley (early Visean)

Outcrops of the Garleton Hills Volcanic Formation of East Lothian lie entirely between the projected north-easterly continuation of the Southern Upland Fault at depth and NE-trending splays to the south-east, such as the Dunbar–Gifford Fault (McAdam and Tulloch, 1985; Davies *et al.,* 1986). They therefore overlie Lower Palaeozoic rocks of the Southern Uplands terrane at no great depth. Superb coastal exposures around North Berwick show the relationships of the basal basaltic pyroclastic rocks to associated necks and sedimentary country rocks (see North Berwick Coast GCR site report), and overlying basaltic to trachytic lavas form the Garleton Hills (see GCR site report). The sequence is up to 520 m thick. Thinner successions have been encountered to the south-west in the Spilmersford and D'Arcy boreholes and in a small outcrop near Borthwick, still within the same fault-bound block.

Some flows of analcime trachybasalt in East Lothian appear to have contained leucite originally (Bennett, 1945). Apart from one other flow in the Campsie Fells, which is phonolitic, these are the only known silica-undersaturated evolved lavas in the Dinantian lava successions. However, the East Lothian lava field is unusual because of its apparent association, hacked by limited K-Ar whole-rock dates (De Souza, 1974, 1979), with several large high-level intrusions (plugs and laccoliths) of silica-undersaturated phonolitic rocks. The latter form the prominent landmarks of Traprain Law, North Berwick Law and the Bass Rock (e.g. see (Figure 2.6) — North Berwick Coast GCR site report) as well as a sill at Hairy Craig (Bailey in Clough *et al.,* 1910; MacGregor and Ennos, 1922; Campbell and Stenhouse, 1933; McAdam and Tulloch, 1985). They are represented by the Traprain Law GCR site.

In Edinburgh, the lavas around Arthur's Seat and Calton Hill, together with associated intrusions such as the Lion's Head and Lion's Haunch vents and the basalt plug of the Castle Rock, dominate the city landscape, and the Arthur's Seat Volcano GCR site is one of the most widely appreciated geological localities in Britain. At least 13 lavas, ranging from olivine-clinopyroxene-phyric basalts to hawaiite and mugearite, form a succession 400–500 m thick (Clark, 1956; Black, 1966). A more restricted, 90 m-thick succession of tuffs and olivine-clinopyroxene-phyric basalts forms Craiglockhart Hill, 6 km to the south-west. Together these volcanic sequences comprise the Arthur's Seat Volcanic Formation.

Burntisland and Bathgate Hills (early Visean to Namurian)

In the Burntisland area of Fife, two volcanic developments within the Anstruther Formation are probably younger than the Arthur's Seat and Garleton Hills volcanic formations of the Lothians (Figure 2.1). At the base of the formation, the Charles Hill Volcanic Member consists of tuffs and olivine-microphyric basalts that crop out on the limbs of a shallow anticline centred upon the island of Inchcolm. The higher unit, of coarse tuffs and agglomerates, is known from boreholes and poor exposures onshore to the north. Major outcrops of late Visean volcanic rocks occur around the Burntisland Anticline, where up to 485 m of olivine-microphyric basalt lavas ('Dalmeny' and 'Hillhouse' types) with subordinate pyroclastic rocks and volcaniclastic sedimentary rocks constitute the Kinghorn Volcanic Formation. This formation, which is represented onshore by the Burntisland to Kinghorn Coast GCR site, is also well developed offshore to the east, as was seen

underground in Seafield Colliery, and on the island of Inchkeith in the Firth of Forth. The succession is dominantly subaerial, but with periodic submergence beneath freshwater lakes or marine incursions during which some pillow lavas and hyaloclastites were formed.

Within and around the West Lothian oil-shale field, volcanic activity was of a distinctly different nature to the generally earlier Visean activity elsewhere in the Midland Valley. In contrast to the wide compositional variety within the Garleton Hills and most Clyde Plateau successions, this volcanism was entirely basaltic. Initial activity may have been contemporaneous with later phases of the essentially subaerial Clyde Plateau Volcanic Formation, but subsequently the terrestrial lava pile was overlapped and the volcanism continued to develop in a coastal-plain–lagoonal–shallow-marine environment that was a precursor to Silesian volcanic settings. The earlier phases of this activity are poorly exposed and much information has come from boreholes and underground workings (Mitchell and Mykura, 1962). Although later lavas are well exposed in parts of the Bathgate Hills, no suitable GCR site has been identified.

The Crosswood Ash, known from exposures and boreholes around Crosswood Reservoir, occurs at the base of the West Lothian Oil-shale Formation, and the 100 m-thick Seafield–Deans Ash of the West Calder area underlies the freshwater Burdiehouse Limestone that marks the base of the Hopetoun Member slightly higher in that formation. Other thin but widespread volcaniclastic beds occur within the Hopetoun Member (e.g. the Port Edgar Ash and Barracks Ash) and a basalt lava occurs at this general stratigraphical level near Carlops, in the Midlothian Basin. Farther west, in an oil-well at Salsburgh in the Central Coalfield, supposed Lower Devonian volcanic rocks are overlain by 100 m of basaltic tuffs and lavas with interbeds of limestone and mudstone that have been termed the 'Salsburgh Volcanic Formation' (Cameron *et al.,* 1998). These are succeeded directly by the Burdiehouse Limestone and hence are probably contemporaneous with the Seafield–Deans Ash.

Higher still in the Hopetoun Member, above the Houston Marls, thick and widespread pyroclastic rocks mark the base of the Bathgate Hills Volcanic Formation. Beneath the Central Coalfield to the west, in the Rashiehill Borehole, this major volcanic formation rests directly upon the Clyde Plateau Volcanic Formation. In the Bathgate Hills area it interdigitates with the Visean sedimentary succession and extends well into the Namurian, accumulating a total thickness of about 600 m of volcanic rocks (Cadell, 1925; Smith *et al.,* 1994; Stephenson in Cameron *et al.,* 1998). Rather than split the description between chapters, the formation is described in its entirety in the 'Introduction' to Chapter 4.

The western Midland Valley (early Visean)

The Clyde Plateau Volcanic Formation comprises the major part of the Strathclyde Group in the western Midland Valley. Its extensive main outcrop encircles Glasgow on three sides, forming the Touch, Fintry and Gargunnock hills, the Campsie Fells and the Kilpatrick Hills to the north, and the Renfrewshire Hills, the Beith–Barrhead Hills and the Dunlop–Eaglesham–Strathaven Hills to the south (Figure 2.2). The outcrop is divided by major faults into several discrete 'blocks', each with its own succession. Most have been described in some detail in Geological Survey memoirs and some attempt has been made to correlate parts of successions between blocks, although in some cases this is extremely tentative (Figure 2.4).

In the north-east of the outcrop the Gargunnock, Touch and Fintry hills form a coherent block (the Fintry–Touch Block, see (Figure 2.4)) with a volcanic sequence that is 300–400 m thick. The lavas are mainly of feldspar-phyric basalts and hawaiites ('Markle' and jedburgh' types), with subordinate trachybasalts and mugearites (Read in Francis *et al.,* 1970). Volcanic necks and proximal volcaniclastic rocks are rare, so the Touch, Fintry and Gargunnock Hills GCR site represents part of the Clyde Plateau Volcanic Formation that may have originated mainly from fissure eruptions. The Campsie Fells, Kilsyth Hills and Denny Muir, forming the next block to the south-west (the Campsie Block), have a sequence in excess of 500 m thick. A wide range of lava compositions from olivine-clinopyroxene-phyric basalts to trachyte and a rare phonolitic trachyte are represented, though here too feldspar-phyric basalts and hawaiites are dominant and parts of the succession can be traced into the Touch Hills (Craig, 1980; Hall in Forsyth *et al.,* 1996; Hall *et al.,* 1998). Numerous volcanic necks are concentrated along four NE-trending 'linear vent systems' and the Campsie Fells GCR site has been selected to represent this multiple vent volcanism. To the east of the GCR site is the major Waterhead Central Volcanic Complex, which dominated the later extrusive phases and may have developed a caldera.

The sequence in the Kilpatrick Hills Block is separated from that of the Campsie Fells by the E–W-trending Campsie Fault, and correlations between these two blocks are only tentative. The 400 m-thick Kilpatrick sequence includes many olivine- and olivine-clinopyroxene-phyric basalts ('Dalmeny, 'Dunsapie' and 'Craiglockhare types) and is generally more mafic than that of the Campsie Block. Many lavas thin eastwards towards Strath Blane, where Hall *et al.* (1998) suggested that high ground, possibly formed by early tephra cones, formed a barrier. Later lavas, possibly emanating from the Waterhead Central Volcanic Complex, can be correlated across Strath Blane, suggesting that the barrier had become ineffective by this time. Many of the lavas in the Kilpatrick Hills originated from small central volcanoes, now represented by necks and plugs. Most of them lie on south-west continuations of the Campsie linear vent systems, and in the far south-west is Dumbarton Rock, selected for the GCR as representative of a volcanic plug associated with the Clyde Plateau Volcanic Formation.

Some of the upper lavas in the western Kilpatrick Hills appear to be continuous across the River Clyde and have been correlated with various higher parts of the Renfrewshire Hills succession. The maximum thickness of the Clyde Plateau Volcanic Formation, up to 1000 m, is attained in the Renfrewshire Hills (Stephenson in Paterson *et al.,* 1990), although this thins markedly southwards towards Ardrossan in the contiguous Kilbirnie Hills (Stephenson in Monro, 1999). Much of the succession consists of alternating flows of feldspar-phyric hawaiites ('Markle' type) and aphyric mugearites, and these two lithologies commonly occur together in composite flows, as represented by the Dunrod Hill GCR site. The Misty Law Trachytic Centre is a major feature in the middle of the succession (Johnstone, 1965) and minor trachytic rocks and rhyolites occur at higher levels. Across the fault zone of the Paisley Ruck, to the south-east, the lava sequence in the Beith–Barrhead Hills is probably less than 300 m thick, being arranged in a gentle SW-plunging anticline. The varied but essentially basaltic lavas may be equivalent to only the upper, more mafic part of the adjoining Renfrewshire Hills succession (Stephenson in Paterson *et al.,* 1990; in Hall *et al.,* 1998; and in Monro, 1999). This contrasts with the view of De Souza (1979), based on K-Ar age determinations (337 ± 7 Ma, or *c.* 344 Ma using new constants) and with the Ar-Ar date of 335 ± 2 Ma (AA. Monaghan and M.S. Pringle, pers. comm., 2002), which both suggest that the Beith Hills include some of the oldest lavas of the Clyde Plateau Volcanic Formation. Farther south-east, across the Dusk Water Fault, lies a vast outcrop of poorly exposed varied volcanic rocks that form undulating high moorland between Dunlop, Eaglesham and Strathaven. Their stratigraphy and structure are difficult to determine but thickness estimates range from 500 m to 900 m and a full range of lithologies is present, from mafic basalts to trachyandesites, trachytes and rhyolites (Richey *et al.,* 1930; Paterson *et al.,* 1998; MacPherson *et al.,* 2001). Towards the east of this block, widespread proximal pyroclastic rocks and volcaniclastic sedimentary rocks, associated with trachytic lavas and plugs, constitute the Gowk Stane Member. Numerous other trachytic plugs and necks lie on NE- and NW-trending lineaments throughout the block, and there are several plugs or laccoliths of silica-undersaturated phonolitic trachyte, such as that which forms the prominent landmark of Loudoun Hill, near Darvel. Basaltic plugs are less common in this block.

The widespread volcanic outcrops terminate abruptly in the south-east at the Inchgotrick Fault, but the Heads of Ayr Neck on the south Ayrshire coast (Whyte, 1963b) may represent a small isolated volcano of similar age to the Clyde Plateau Volcanic Formation (see Heads of Ayr GCR site report).

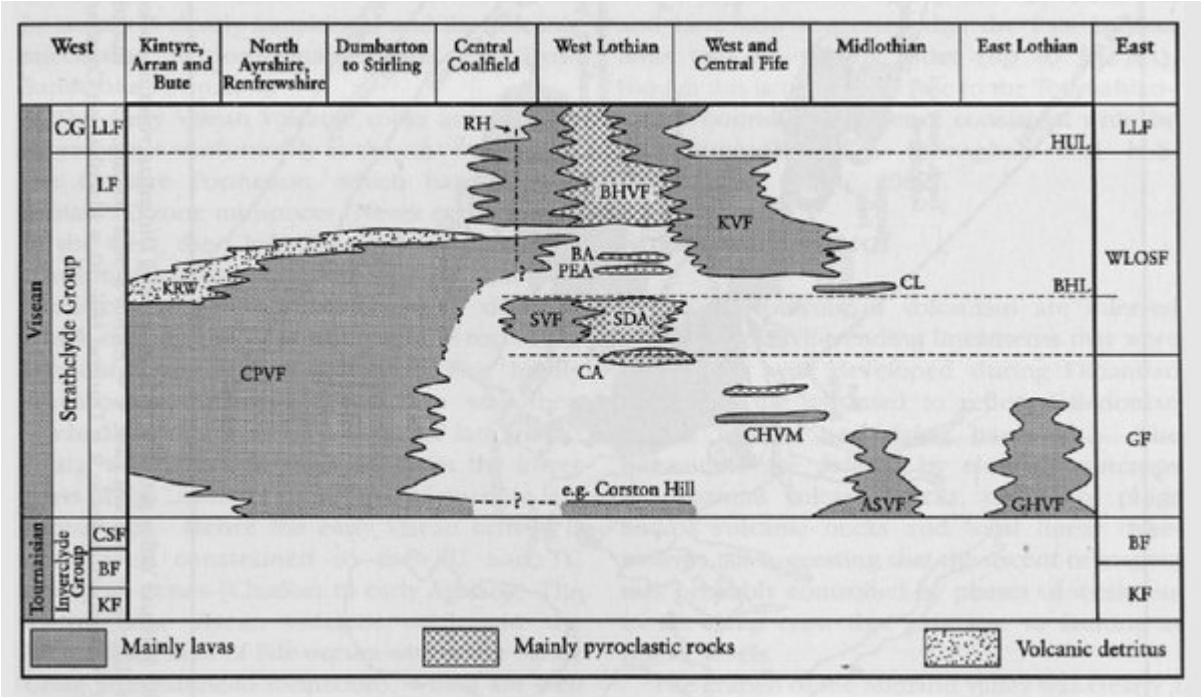
It is probable that the original lava fields of the Clyde Plateau did not extend significantly farther to the north-west than the present outcrops (George, 1960; Whyte and MacDonald, 1974), although they do spill to a minor extent across the Highland Boundary Fault on Ben Bowie near Helensburgh (Paterson *et al.,* 1990). To the west, outlying lava successions on the islands of Little Cumbrae, Bute and Arran are thin, suggesting that there was dramatic attenuation westwards from the main outcrops. Significantly, on Bute and Arran, up to 16 m of fluvio-deltaic mudstones with sandstones and thin coals occur beneath the volcanic rocks, but with a sharp erosional base above the Clyde Sandstone Formation, suggesting that the onset of volcanism was a little later here than in the main outcrop. However, in south Kintyre a highly varied volcanic succession, ranging from mafic basalts to trachyte and up to 400 m thick, rests upon the Kinnesswood Formation, Lower Old Red Sandstone and Dalradian rocks, northwest of the Highland Boundary Fault (McCallien, 1927). The Kintyre succession is overlain unconformably by volcaniclastic detritus akin to the Kirkwood Formation and by Lower Limestone Formation strata and hence has been assigned to the Clyde Plateau Volcanic Formation, though it is likely that it constitutes an entirely separate lava field (see Machrihanish Coast and South Kintyre GCR site report). In fact it is closer to the Visean volcanic rocks at Ballycastle in Northern Ireland (Wilson and Robbie, 1966) than it is to the main outcrops of the Clyde Plateau.

East of Stirling, thin sequences of tuffs, basalts and felsic lavas close to the Ochil Fault near Dollar (Browne and Thirlwall, 1981) and in the Cleish Hills (Geikie, 1900) are possibly contemporaneous with the Clyde Plateau Volcanic Formation, but separate from the main development. However, the formation is assumed to be continuous beneath the Central Coalfield Syncline and is present at the base of the Rashiehill Borehole, near Slamannan (Anderson, 1963). Seismic evidence suggests that it thins abruptly farther to the east, and is replaced by the thick sedimentary succession of the West Lothian oil-shale field (Hall, 1971). Around the southern rim of the oil-shale field, Francis (1991) suggested that the lowest lavas of the Clyde Plateau Volcanic Formation may be represented by thin sequences in poorly exposed ground around Carstairs and on the north-west flanks of the Pentland Hills (e.g. Corston Hill, Torweaving Hill, Cockburnhill), and that these impersistent outcrops may be contemporaneous with the volcanic rocks of Edinburgh (Mitchell and Mykura, 1962).

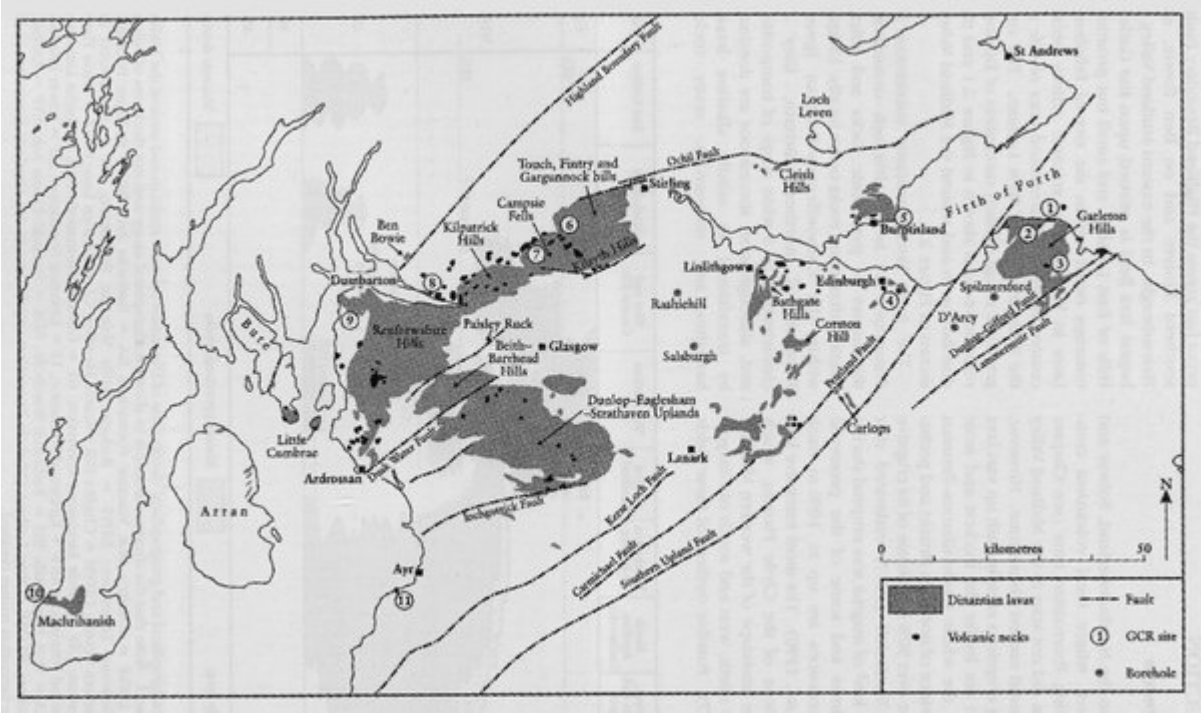
Highlands

In the northern Highlands, alkaline lampro-phyre dykes with an approximate east–west trend (see 'Introduction' to Chapter 5) include some that have been assigned an age of *c.* 326 Ma (Baxter and Mitchell, 1984; Esang and Piper, 1984), making them contemporaneous with some of the Visean activity farther south. It is therefore possible that some of the diatremes in the northern Highlands that appear to be associated with these dykes are also of Visean age (see 'Introduction' to Chapter 4).

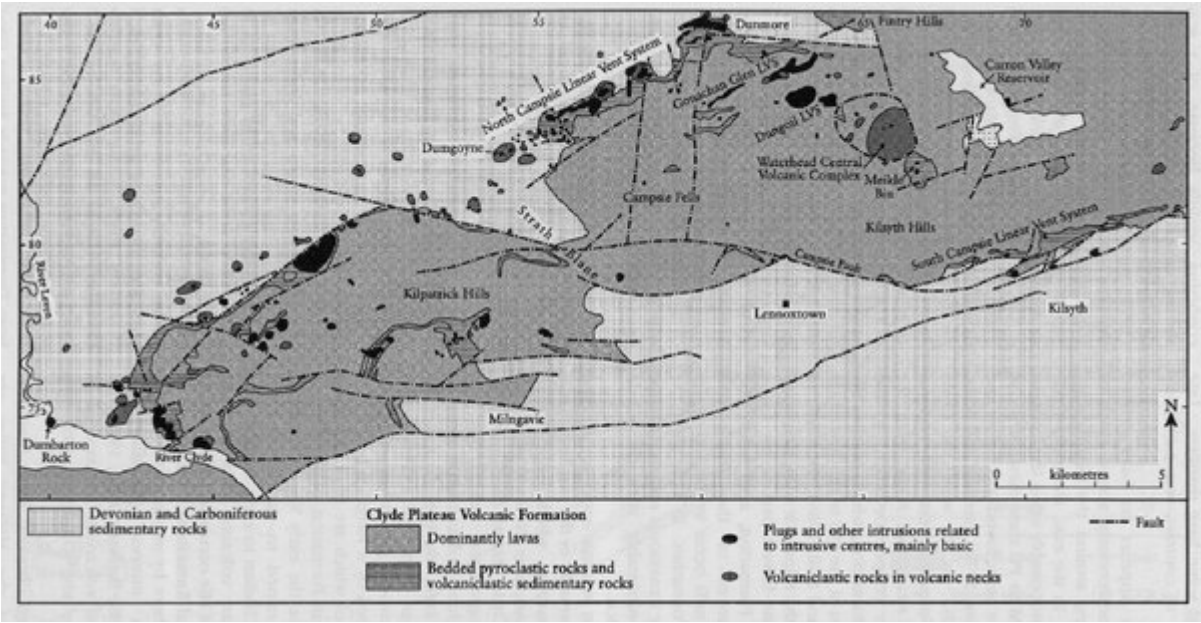
References



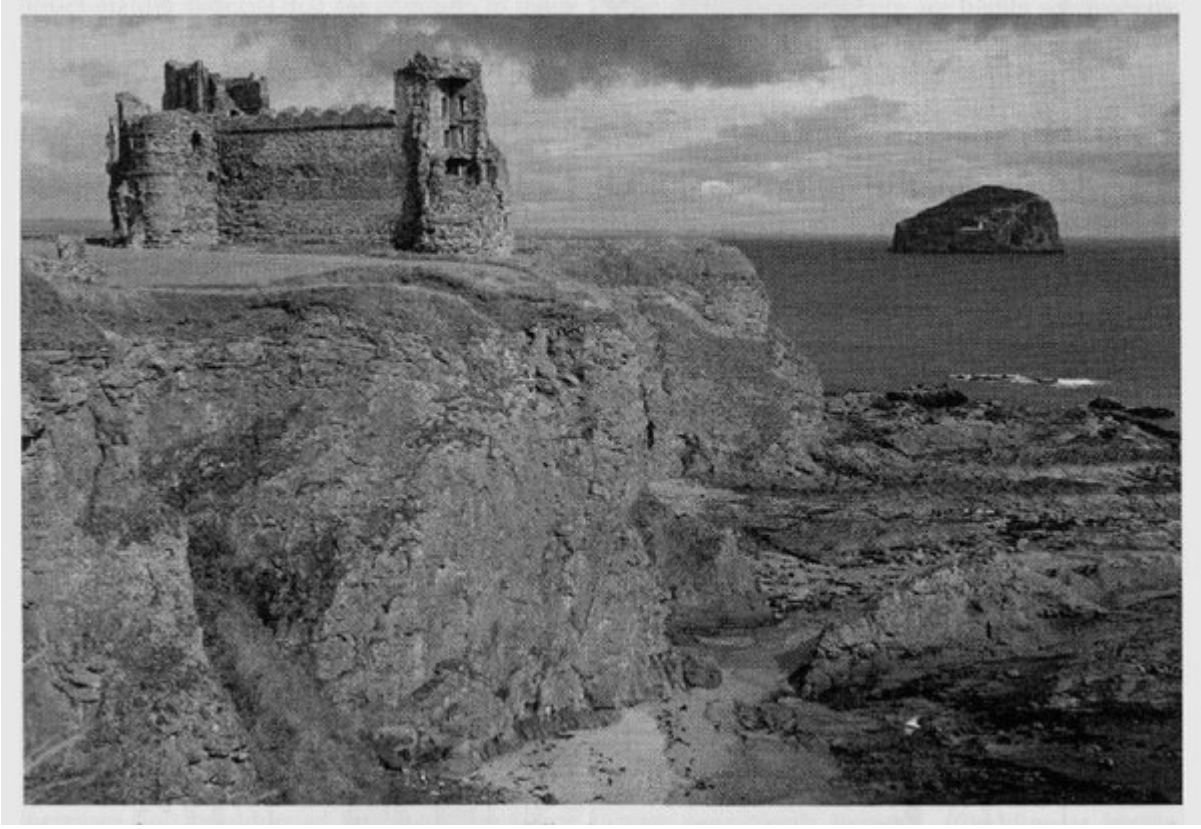
(Figure 2.1) Stratigraphical and geographical distribution of Dinantian volcanic rocks in and around the Midland Valley of Scotland. Note that the diagram attempts to show stratigraphical range and not thickness of volcanic successions. (ASVF = Arthur's Seat Volcanic Formation; BA = Barracks Ash; BF = Ballagan Formation; BHL = Burdiehouse Limestone; BHVF = Bathgate Hills Volcanic Formation; CA = Crosswood Ash; CG = Clackmannan Group; CHVM = Charles Hill Volcanic Member; CL = Carlops Lava; CPVF = Clyde Plateau Volcanic Formation; CSF = Clyde Sandstone Formation; GF = Gullane Formation; HUL = Hurlet Limestone; KF = Kinnesswood Formation; KRW = Kirkwood Formation; LF = Lawmuir Formation; LLF = Lower Limestone Formation; PEA = Port Edgar Ash; RH = Rashiehill Borehole; SDA = Seafield–Deans Ash; SVF = Salsburgh Volcanic Formation; WLOSF = West Lothian Oil-shale Formation (equivalent to the Aberlady



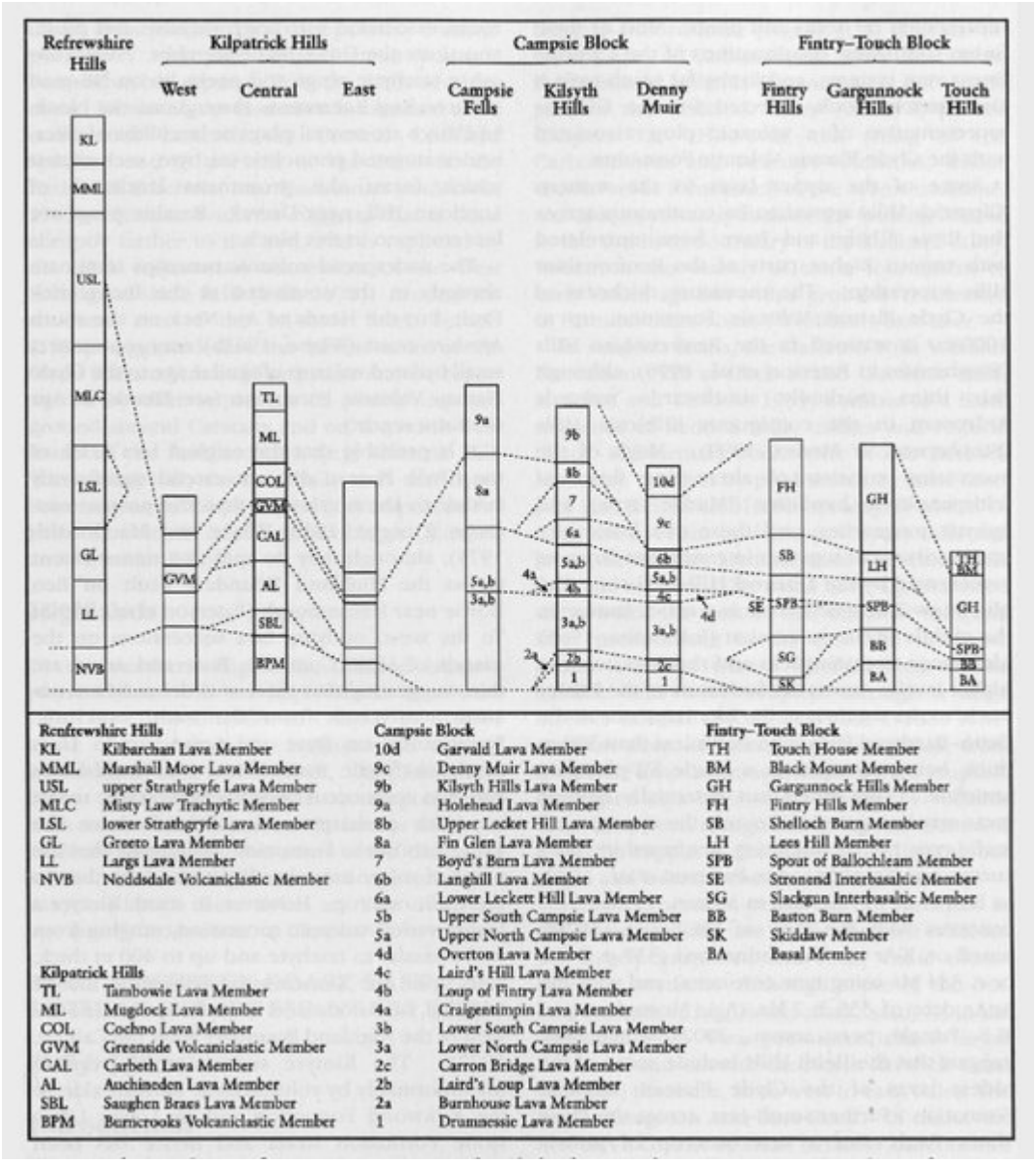
(Figure 2.2) Map of the Midland Valley showing the outcrops of Dinantian volcanic rocks and the major structural components. GCR sites: 1 = North Berwick Coast; 2 = Garleton Hills; 3 = Traprain Law; 4 = Arthur's Seat Volcano; 5 = Burntisland to Kinghorn Coast; 6 = Touch, Fintry and Gargunnock Hills; 7 = Campsie Fells; 8 = Dumbarton Rock; 9 = Dunrod Hill; 10 = Macrihanish Coast and South Kintyre; 11 = Heads of Ayr. After Cameron and Stephenson (1985).



(Figure 2.3) Map of the Kilpatrick Hills and Campsie Fells, showing outcrops of the Clyde Plateau Volcanic Formation and volcanotectonic lineaments defined by plugs, necks and proximal volcaniclastic beds. The most prominent lineament, along the north-west edge of the volcanic outcrops, is the Dumbarton–Fintry Line of Whyte and MacDonald (1974). Based on British Geological Survey 1:50 000 sheets 30W, Greenock (1990); 30E, Glasgow (1993); and 31W, Airdrie (1992).



(Figure 2.6) Tantallon Castle, on agglomerate cliffs of the Tantallon Vent, North Berwick Coast GCR site, with the phonolitic trachyte plug of the Bass Rock beyond. (Photo: British Geological Survey, No. D3665, reproduced with the permission of the Director, British Geological Survey, NERC.)



Renfrewshire Hills

KL	Kilbarchan Lava Member
MML	Marshall Moor Lava Member
USL	upper Strathgryfe Lava Member
MLC	Misty Law Trachytic Member
LSL	lower Strathgryfe Lava Member
GL	Greeto Lava Member
LL	Largs Lava Member
NVB	Noddsdale Volcaniclastic Member

Kilpatrick Hills

TL	Tambowie Lava Member
ML	Mugdock Lava Member
COL	Cochno Lava Member
GVM	Greenside Volcaniclastic Member
CAL	Carbeth Lava Member
AL	Auchineden Lava Member
SBL	Saughen Braes Lava Member
BPM	Burncrooks Volcaniclastic Member

Campsie Block

10d	Garvald Lava Member
9c	Denny Muir Lava Member
9b	Kilsyth Hills Lava Member
9a	Holehead Lava Member
8b	Upper Lecket Hill Lava Member
8a	Fin Glen Lava Member
7	Boyd's Burn Lava Member
6b	Langhill Lava Member
6a	Lower Leckett Hill Lava Member
5b	Upper South Campsie Lava Member
5a	Upper North Campsie Lava Member
4d	Overton Lava Member
4c	Laird's Hill Lava Member
4b	Loup of Fintry Lava Member
4a	Craigentimpin Lava Member
3b	Lower South Campsie Lava Member
3a	Lower North Campsie Lava Member
2c	Carron Bridge Lava Member
2b	Laird's Loup Lava Member
2a	Burnhouse Lava Member
1	Drumnessie Lava Member

Fintry–Touch Block

TH	Touch House Member
BM	Black Mount Member
GH	Gargunnock Hills Member
FH	Fintry Hills Member
SB	Shelloch Burn Member
LH	Lees Hill Member
SPB	Spout of Ballochleam Member
SE	Stronend Interbasaltic Member
SG	Slackgun Interbasaltic Member
BB	Baston Burn Member
SK	Skiddaw Member
BA	Basal Member

(Figure 2.4) Correlation of composite sections in the Clyde Plateau Volcanic Formation. Based on information in Forsyth et al. (1996); Hall et al. (1998); and Paterson et al. (1990). N.B. formal designation of these units as members is currently in progress.