Carboniferous and Permian Igneous Rocks of Great Britain

North of the Variscan Front

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Chapter 4

Silesian and Early Permian volcanic rocks of Scotland

INTRODUCTION

D. Stephenson

Volcanism continued intermittently throughout Dinantian time in the Midland Valley of Scotland, but as the sedimentary basins developed and the palaeogeography changed from fluvial plains with lakes to deltas, estuaries and shallow seas, so the nature of the volcanism changed. The vast subaerial lava plateaux and linear eruptive centres that dominated earlier Dinantian times were replaced in later Dinantian and Namurian times by more localized, short-lived, central vent complexes, characterized by more explosive, phreatomagmatic eruptions. Pyroclastic deposits are a major product of these eruptions and the lavas are almost exclusively basaltic (of microporphyritic 'Dalmeny' and 'Hillhouse' types); many are silica-undersaturated alkali olivine basalts and basanites. Basaltic hawaiites are rare, and the more fractionated rocks that are a feature of many early Dinantian successions, are absent.

These volcanic conditions were already widely established by the beginning of Namurian time and continued intermittently until at least mid-Westphalian times in the eastern Midland Valley, though at an overall less productive level than in Dinantian times. In the western Midland Valley, volcanism ceased following a major outpouring of lavas in late Namurian to earliest Westphalian times. Since there are no strata of Stephanian age preserved in Scotland we cannot be certain if there was any volcanism at this time. Large volumes of tholeiitic magma were intruded as dykes and sill-complexes during early Stephanian times (see Chapter 6) but, according to the model of Francis (1982), the magma was under insufficient pressure to reach the surface and there is no evidence of it having done so. Volcanism did resume in latest Stephanian or very early Permian times, when conditions had once again become continental, with localized outpourings of alkali basalt and basanite lavas in western and south-western areas and possibly also in the eastern Midland Valley where some sub-volcanic plugs and necks have late Stephanian to Early Permian radiometric ages.

Most of the Silesian volcanic rocks are interbedded with well-established, commonly fossiliferous, shallow-water sedimentary successions, and it is relatively easy to trace their stratigraphical development (Figure 4.1).

Lavas dominate volcanic successions in the early Namurian rocks of the Bathgate Hills, the late Namurian rocks of north Ayrshire and the Early Permian rocks of south-west Scotland (Figure 4.2). Other eruptions were predominantly of pyroclastic rocks and these are

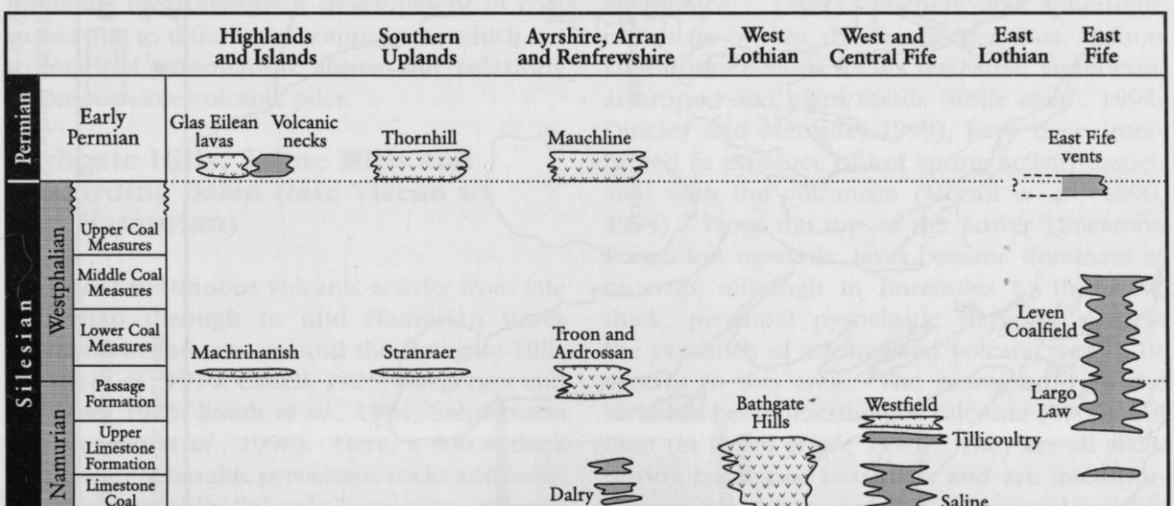

Figure 4.1 Range and distribution of the Silesian and Early Permian volcanic rocks of Scotland. After, in part, Cameron and Stephenson (1985).

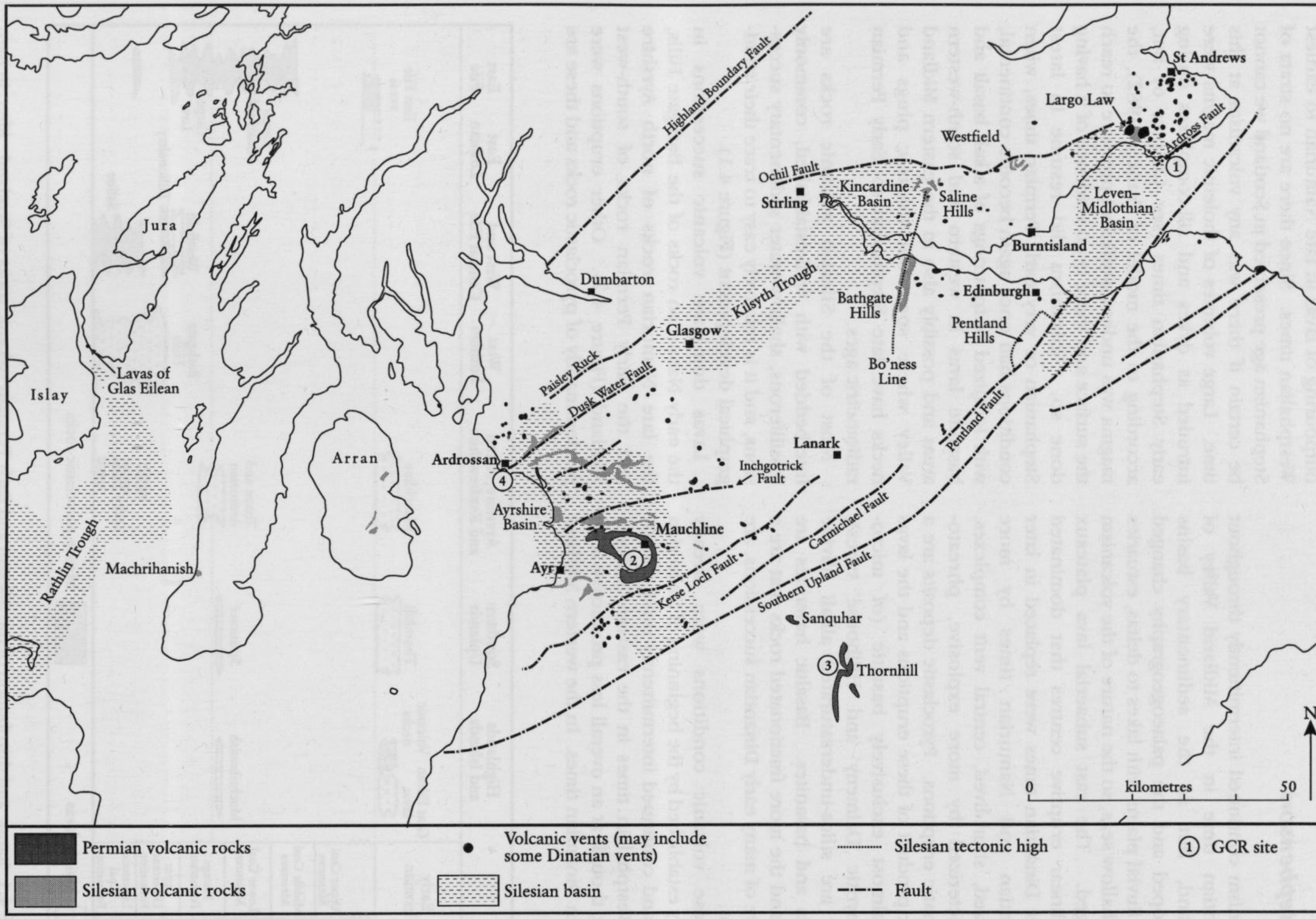

Figure 4.2 Map of central and southern Scotland showing the main outcrops of Silesian and Permian volcanic rocks. GCR sites: 1 = East Fife Coast; 2 = Howford Bridge; 3 = Carron Water; 4 = Ardrossan to Saltcoats Coast. Information from published sources, including Cameron and Stephenson (1985); Francis (1991); Read (1988); and Rippon *et al.* (1996).

represented only by sub-volcanic necks and beds of ash-fall tuff. However, throughout Silesian times, large volumes of magma solidified at depth as sill-complexes (see Chapter 5). It is likely that the increasing thickness of geotechnically weak sediments in the rapidly developing Silesian basins would be of too low density to support columns of magma, which spread laterally as sills (Francis, 1991). Magma that did have sufficient energy to rise to shallower levels reacted with groundwater and wet sediment to produce violent, phreatomagmatic eruptions. Such eruptions took place largely in areas of shallow water close to low-lying coastal plains. Here, accumulations of sediment and volcanic rocks broadly kept pace with subsidence, but periodically the volcanic rocks would build up above sea level where they were subjected to subaerial weathering, lateritization, erosion and re-deposition as volcaniclastic sediments. As the balance between rates of eruption, erosion and subsidence changed, so the relationships between the volcanic rocks and sediments within the preserved successions varied (Francis, 1961a,b, 1991). Since many of these successions include coal-bearing strata, studies of the volcanic rocks have had vital economic implications. Accumulations of volcanic rocks are commonly surrounded by shoals of volcaniclastic sand, and together these locally 'interrupt' the continuity of otherwise widespread contemporaneous coal seams. They also continued to influence the subsequent development of coal seams due to differential compaction, which led to marked attenuation above the relatively incompressible volcanic piles.

Bathgate Hills, Saline Hills and Kincardine Basin (late Visean to mid Namurian)

The most continuous volcanic activity from late Dinantian through to mid Namurian times occurred in the area around the Bathgate Hills (Peach *et al.*, 1910; Cadell, 1925; Macgregor and Haldane, 1933; Smith *et al.*, 1994; Stephenson in Cameron *et al.*, 1998). Here, a 600 m-thick succession of basaltic pyroclastic rocks and lavas, the Bathgate Hills Volcanic Formation, extends from the upper part of the Hopetoun Member, West Lothian Oil-shale Formation, to just above the Castlecary Limestone at the base of the Passage Formation. Unfortunately, there are no reliable radiometric dates for this prolonged sequence, which spans the Dinantian–Silesian boundary; some precise Ar-Ar determinations would have clear international value. This important and extensive sequence is not represented at present by a GCR site.

Borehole and mining information to the west of the outcrop suggests that the volcanic deposits are restricted to a sub-circular area, 20–25 km in diameter, that coincides with spectacular positive gravity and magnetic anomalies. The source of these anomalies has been the subject of much debate, as the combined thickness of volcanic rocks (Bathgate Hills and earlier volcanic formations) is insufficient to generate the observed anomalies. Current interpretations favour up to 1 km of volcanic rocks, intruded in their lower part by a large basic mass extending to a depth of about 8 km, and all sited upon a WNW-trending structural high that may have acted as a focus for the igneous activity (Rollin in Cameron *et al.*, 1998). Several necks and plugs that cut older strata to the east of the main outcrop of volcanic rocks give some idea of the former eastward extent of the volcanic field, prior to erosion.

The basal part of the volcanic sequence, up to the base of the Lower Limestone Formation, is predominantly of pyroclastic rocks, except for some more persistent lavas in the Riccarton–Longmuir area. Sporadic graded bedding and load casts suggest subaqueous deposition in places, but numerous seatclays indicate frequent emergence. Layers of chert and spherulitic carbonate within the freshwater East Kirkton Limestone, famous for its terrestrial vertebrate, arthropod and plant fossils (Rolfe *et al.*, 1994; Dineley and Metcalfe, 1999), have been interpreted as evidence of hot spring activity associated with the volcanism (McGill *et al.*, 1990, 1994). From the top of the Lower Limestone Formation upwards, lavas become dominant at outcrop, although in boreholes to the west, thick, proximal pyroclastic deposits suggest the presence of a long-lived volcanic centre or centres in this area. The petrography of the lavas has been described by Falconer (1906) and Flett (in Peach *et al.*, 1910). They are all alkali olivine basalts or basanites, and are microporphyritic with phenocrysts of olivine and variable amounts of augite ('Dalmeny' and 'Hillhouse' type). Kaolinized or reddened flow tops indicate subaerial eruption.

The overall picture of the Bathgate Hills area is of a low-lying, heavily vegetated coastal plain in late Dinantian times, giving way periodically to shallow marine conditions in Lower Limestone and Upper Limestone formation times. Volcanoes accumulated above sea level to form islands surrounded by coastal plains, restricted lagoons and a variety of carbonate reefs, all neatly modelled by Jameson (1987) (see Petershill Quarry GCR site report in the *British Lower Carboniferous Stratigraphy* GCR volume – Cossey *et al.*, in prep). Carbonaceous mudstones and argillaceous limestones, interpreted as having formed in back-reef lagoons, contain synsedimentary Pb-Zn mineralization related to the volcanism (Stephenson, 1983).

The Saline Hills of western Fife are broadly along strike to the NNE of the Bathgate Hills along the Bo'ness High, a zone of relatively low subsidence that forms the eastern margin of the Silesian Kincardine Basin (Read, 1988). Here, thick tuffs, volcaniclastic sedimentary rocks and rare thin basalt flows occur in the Limestone Coal Formation and parts of the Upper Limestone Formation (Francis, 1961a). The succession is cut by several necks and plugs. Within the Kincardine Basin, boreholes and mine workings have revealed distal tuffs at various levels in the Limestone Coal Formation and Upper Limestone Formation that may correlate with the volcanism in the Bathgate Hills to the south (Francis *et al.*, 1961). These are mostly on the eastern side of the basin, on the flank of the Bo'ness High, where several necks have also been recognized (Francis, 1957, 1959; Barnett, 1985). However, a borehole at Tillicoultry in the centre of the basin revealed proximal agglomerates and some lavas in the top part of the Upper Limestone Formation. Rippon *et al.* (1996) have suggested that these were related to the NNE-trending Coalsnaughton Fault which may have been an active extensional fault parallel to the Bo'ness Line.

South-west Scotland (Namurian)

In the west of the Midland Valley, basic pyroclastic rocks are interbedded with sedimentary strata throughout the Limestone Coal Formation and to a lesser extent the Upper Limestone Formation to the west of Dalry; they are known mainly from borehole records (Richey *et al.*, 1930). All may have been derived from necks that cut older strata to the west.

A major episode of volcanism is represented in the upper part of the Passage Formation by the Troon Volcanic Member. This is recognizable over an area that extends from Ayrshire south to Stranraer and west to Arran, Kintyre and possibly to Northern Ireland (Richey *et al.*, 1930, fig. 25), but the main development occurs beneath the Coal Measures of the Ayrshire Basin (Monro, 1999). Outcrops of lava occur on the northern and southern flanks of the basin and the thickest development of over 160 m is just to the north of the town of Troon (Figure 4.3). Isopachs suggest contemporaneous movements along the Inchgotrick and Dusk Water faults. Specific volcanic centres have not been identified and may lie offshore. Miospores from interbedded sedimentary rocks constrain the biostratigraphical age to the KV zone (Kinderscoutian to early Marsdenian) and a minimum K-Ar radiometric age of 305 ± 6 Ma has been estimated by De Souza (1982). More precise Ar-Ar determinations would clearly be very useful at this well-defined point in time, just prior to the development of the major coalfield basins. The volcanic member is represented by the **Ardrossan to Saltcoats Coast** GCR site (see GCR site report).

The Troon Volcanic Member is composed almost entirely of subaerial basaltic lavas (olivine-microphyric, 'Dalmeny' type) with some interbedded sedimentary rocks. Petrographical details were given by MacGregor (in Richey *et al.*, 1930; in Eyles *et al.*, 1949). Like the earlier, Dinantian lavas, these are transitional in nature and range from hypersthene- to nepheline-normative; a few are basanites (Macdonald *et al.*, 1977; Wallis, 1989).

The lavas are generally decomposed, commonly with a characteristic red speckled appearance due to sideritic alteration. More advanced decomposition produces pseudostratified greenish-blue clays, thought to be the result of penecontemporaneous subaerial weathering. This weathering is particularly well developed at the top of the member, and on the northern side of the Ayrshire Basin it grades upwards into aluminous clayrocks interbedded with laminated mudstones, seatclays and coals that together comprise the Ayrshire Bauxitic Clay Member (Wilson, 1922; Eyles *et al.*, 1949; Monro, 1999) (see High Smithstone Quarry GCR site report in the *British Upper Carboniferous Stratigraphy* GCR volume – Cleal and Thomas,

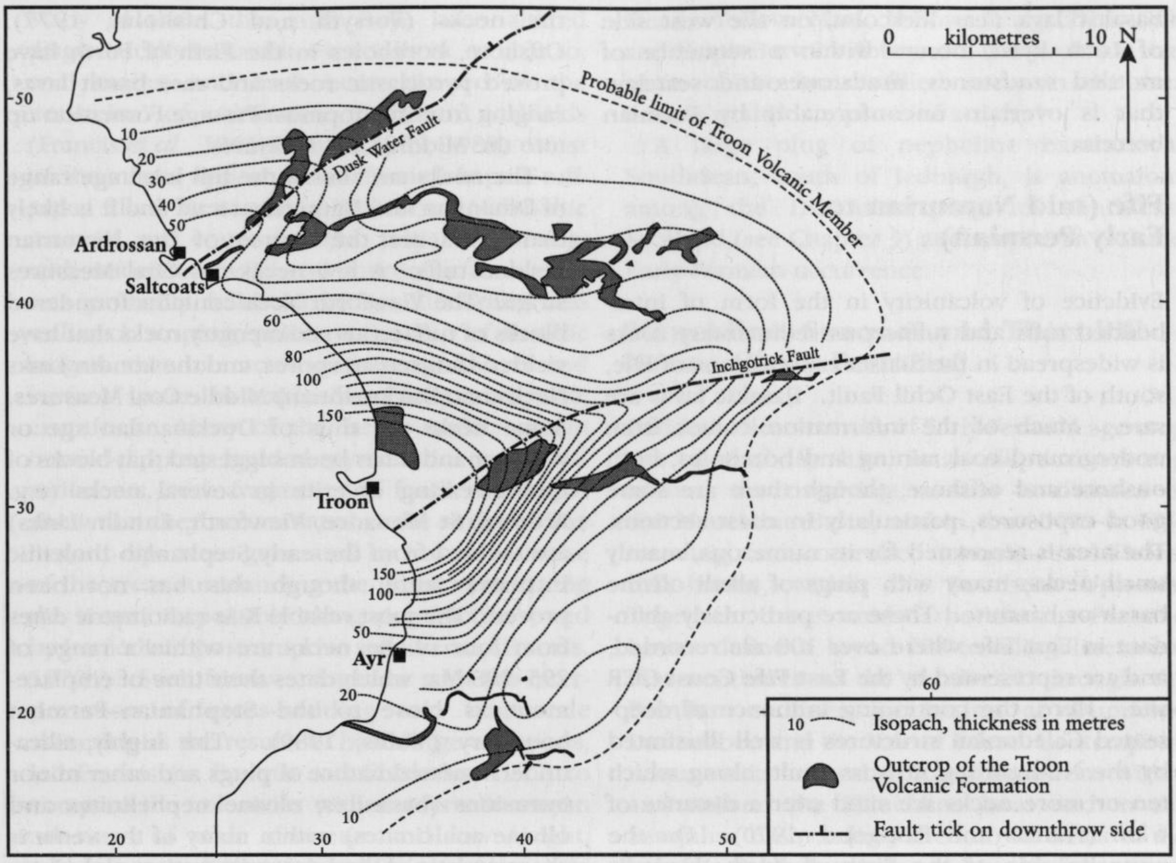

Figure 4.3 Map showing areas of outcrop, and thickness variations, of the Troon Volcanic Member. After Monro (1999); Geological Survey 1:50 000 sheets 14W, Ayr (1978); 14E, Cumnock (1976); and British Geological Survey 1:50 000 Sheet 22E, Kilmarnock (1999).

1996). This complex member is up to 20 m thick in places, but is more typically 2–4 m thick and has been extracted as a source of alum and specialist refractory clay. It contains some of the highest quality fireclay in Britain, with up to 42% Al_2O_3. Whilst the basal parts were undoubtedly formed by the weathering of basalt *in situ*, there has been much debate about additional sedimentary and diagenetic processes that may have operated (Monro *et al.*, 1983). Bauxitic laterites only form in tropical climates and require a significant time to build up any thickness. A variety of clastic clayrocks demonstrate the local reworking of the weathered crust and, in the absence of any other sediment input, we can deduce that the topography of the underlying lava surface was low. Coals, seatrocks and plant remains, including tree trunks, are abundant and, together with the presence of at least one marine band, suggest that the area was reduced to a heavily vegetated, flat, low-lying coastal plain when the volcanism ended at the close of Namurian time.

To the west of the main outcrop, on the Isle of Arran, a thin succession of red tuff and basaltic lava overlain by bauxitic clays and Middle Coal Measures occurs in the Merkland Burn, near Brodick Castle. Tuffs with thin lavas occur in two outcrops to the west and WSW of Lamlash: in the Benlister Burn, bauxitic clays are found and in the larger outcrop at the head of the Sliddery Water, tuffs are overlain by red mudstones with mussels of Middle Coal Measures type (Leitch, 1942). Both occurrences have been assigned to the Passage Formation. Farther west, in Kintyre, about 100 m of thick basaltic lavas with thin tuffs and red lateritic mudstones are known only from boreholes at Machrihanish. The highest lavas have been weathered to bauxitic clay and there is a marked non-sequence beneath the overlying Lower Coal Measures. In Galloway, a single thin flow of basaltic lava near Kirkcolm, on the west side of Loch Ryan, occurs within a sequence of mottled sandstones, mudstones and seatclays that is overlain unconformably by Permian breccias.

Fife (mid Namurian to Early Permian)

Evidence of volcanicity in the form of interbedded tuffs and tuffaceous sedimentary rocks is widespread in the Silesian successions of Fife, south of the East Ochil Fault. Basaltic lavas are rare. Much of the information comes from underground coal mining and boreholes, both onshore and offshore, though there are some good exposures, particularly in coast sections. The area is renowned for its numerous, mainly small necks, many with plugs of alkali olivine basalt or basanite. These are particularly abundant in East Fife where over 100 are recorded, and are represented by the **East Fife Coast** GCR site. Here, the continuing influence of deep-seated Caledonian structures is well illustrated by the NE-trending Ardross Fault, along which ten or more necks are sited over a distance of 4 km (Francis and Hopgood, 1970). On the opposite side of the Firth of Forth, Howells (1969) recorded high-level vent structures near Longniddry that cut Namurian strata and lie directly on the projected north-eastwards continuation of the Southern Upland Fault, which may have controlled the rise of magma during Visean time (see Chapter 2). The East Fife necks are also renowned as some of the most productive sources in Scotland of megacrysts and/or rock clasts of deep-seated igneous material or metamorphic basement (e.g. Colvine, 1968; Chapman, 1974, 1976; Macintyre *et al.*, 1981; Donaldson, 1984) (see Chapter 1).

Onshore outcrops of interbedded volcanic rocks are concentrated mainly in two areas. Around the former Westfield opencast coal site in central Fife, there are five flows of basaltic pillow lava with associated tuffs and hyaloclastites in the top of the Upper Limestone Formation and the basal Passage Formation. The large complex necks of Largo Law and Rires in East Fife are surrounded by bedded tuffs and a few lavas that seem to be interbedded with the Upper Limestone Formation and Passage Formation, though in many places it is difficult to separate them from pyroclastic rocks within the necks (Forsyth and Chisholm, 1977). Offshore, boreholes in the Firth of Forth have proved pyroclastic rocks and rare basalt lavas, ranging from the topmost Passage Formation up into the Middle Coal Measures.

The necks cut almost the full local age range of Dinantian and Namurian strata and it is likely that some are the source of the Namurian bedded tuffs. A few necks cut Coal Measures strata. The Viewforth Neck contains foundered blocks of tuffaceous sedimentary rocks that have yielded Langsettian spores, and the Lundin Links Neck cuts (Duckmantian) Middle Coal Measures. Some necks are thus of Duckmantian age or younger and it has been suggested that blocks of quartz-bearing dolerite in several necks (e.g. Ardross, St Monance, Viewforth, Lundin Links) are derived from the early Stephanian tholeiitic intrusive suite, though this has not been proved. The most reliable K-Ar radiometric dates from four of the necks are within a range of 295–288 Ma, which dates their time of emplacement as close to the Stephanian–Permian boundary (Wallis, 1989). The highly silica-undersaturated nature of plugs and other minor intrusions (basanites, olivine nephelinites and olivine analcimites) within many of the vents is characteristic of the latest magmatism elsewhere in the Carboniferous–Permian Igneous Province of northern Britain, especially the undoubted Early Permian lavas and associated necks of south Ayrshire (see below), and hence is compatible with the age estimates.

The morphology and physical volcanology of the Fife volcanoes and their relationships to surrounding contemporaneous sedimentation have been studied more intensively than in any other part of the Carboniferous–Permian Igneous Province of northern Britain. Much of this work has been by E.H. Francis, building upon earlier Geological Survey work and making extensive use of boreholes and mine sections (Francis, 1960, 1961b,c, 1968a,b, 1970b; Francis *et al.*, 1961; Francis and Ewing, 1961; Francis and Hopgood, 1970; Francis in Forsyth and Chisholm, 1977).

The bedded tuffs consist of a mixture of basaltic and comminuted sedimentary debris and are often well graded, indicative of ash fall into shallow water. Thin distal representatives have been traced for up to 30 km from their implied vents and have correlation value as effective time-planes (Francis, 1961c, 1968a).

Many of these thin tuffs have been altered diagenetically to kaolin, especially in, or near to, coal seams, and have been likened to the 'tonsteins' of north-west European coalfields (Francis *et al.*, 1961; Francis, 1969, 1985). Most of the necks appear to be funnel-shaped tuff-pipes filled by varying proportions of basaltic material and country rock. Initial updoming, with associated radial and concentric fracturing, was probably followed by gas-fluxioning and wall-rock stoping, prior to the rise of basaltic magma that interacted with groundwater and surface water in explosive, phreatomagmatic eruptions. Many of the larger necks contain inward-dipping bedded pyroclastic rocks and sediments, with fragments of fossil wood that show that they accumulated at the surface. The inward dips were generated by inward collapse of the areas surrounding the initial vent during the eruption, possibly along ring-fractures, and by immediate post eruptive subsidence (Francis, 1970b). Such features, together with the interpretation of cross-bedding and large-scale slumping as the results of base-surge eruptions, led Francis (in Forsyth and Chisholm, 1977) to compare the volcanoes with modern Surtseyan ash-rings of wide diameter and low height, which are typical of basaltic eruptions into shallow water. Magmas failing to reach the surface were emplaced as a variety of minor intrusions. Details, as illustrated by individual necks, are given in the **East Fife Coast** GCR site report.

East Lothian (?late Stephanian to Early Permian)

The volcanic rocks interbedded with the sedimentary succession of East Lothian are undoubtedly of Dinantian age, as are most of the closely related vents (see **North Berwick Coast** GCR site report). However, some of the associated intrusions are basanitic or foiditic and it seems reasonable to suggest that these may represent a south-eastern continuation of the East Fife late Stephanian to Early Permian volcanic field, from which they are separated by only 15 km. Available K-Ar whole-rock dates are equivocal, but suggest minimum ages in the range 295–229 Ma (Snelling and Chan in McAdam and Tulloch, 1985, recalculated; Wallis, 1989). Notable examples of these intrusions occur at Oldhamstocks, Kidlaw, Limplum, Gin Head, Yellow Man, Yellow Craig Plantation and North Berwick Abbey, and it is probable that some of the breccia-filled necks in the area belong to this late phase of activity.

A large plug of nepheline basanite at Southdean, south of Jedburgh, is anomalous among the Dinantian plugs of south-east Scotland (see Chapter 3) and may be an isolated Early Permian occurrence.

Mauchline, Sanquar and Thornhill basins (Early Permian)

Bedded volcanic rocks of Early Permian age crop out in south Ayrshire, in an elliptical outcrop around the overlying aeolian sandstones of the Mauchline Basin, and in the NNW- to NW-trending, fault-controlled Sanquhar and Thornhill basins, within the Southern Uplands. Together these mid-Carboniferous–Permian basins define a broad NW-trending lineament that continues to the south-east through the Permian sedimentary basins at Dumfries, Lochmaben and the Vale of Eden. Contemporaneous necks and sub-volcanic intrusions within and around the Mauchline lavas and in the Sanquhar Basin extend the known limits of the volcanic fields, but it is not known if they were ever interconnected.

The Mauchline Volcanic Formation, represented by the **Howford Bridge** GCR site, is up to 238 m thick and rests unconformably but with no marked discordance upon the 'Barren Red Beds' of the Upper Coal Measures. Plant debris found near the base of the volcanic sequence suggests an earliest Permian age (Wagner, 1983) and K-Ar whole-rock dates around 286 ± 7 Ma are Early Permian (De Souza, 1982). Palaeomagnetic measurements have also indicated pole positions close to those of Carboniferous–Permian boundary time (Du Bois, 1957; Harcombe-Smee *et al.*, 1996). The lavas are predominantly microporphyritic olivine basalts ('Dalmeny' type), but basanites are common and some strongly silica-undersaturated olivine nephelinites are present. However, analyses include some hypersthene-normative transitional basalts (Macdonald *et al.*, 1977; Wallis, 1989). Pyroclastic rocks comprise a large part of the succession, becoming more abundant in the thicker, eastern parts. Sedimentary rocks within the volcanic sequence contain wind-rounded sand grains, indicating that the lavas were erupted in predominantly desert conditions, but fluvial sandstones and mudstones imply spasmodic sheet-floods and ephemeral lakes.

Over 60 necks are known, mostly within a 20–30 km radius of the centre of the Mauchline Basin, but also extending to West Kilbride in the north (Alexander *et al.*, 1986), Muirkirk in the east and Dalmellington in the south (Figure 4.2). Numerous lines of evidence suggest that these necks are contemporaneous with the lavas and hence delimit the former extent of the volcanic field. Necks are known to cut the Coal Measures succession, post-Coal Measures alkali dolerite sills and the Mauchline Volcanic Formation, but not the overlying Mauchline Sandstone Formation. Many of the necks contain wind-rounded sand grains and some include large subsided blocks of aeolian and fluvial sandstones. Plugs and other vent intrusions are predominantly of highly silica-undersaturated olivine analcimite or monchiquite, but camptonite, basanite and alkali dolerite are also known. Monchiquite dykes, common in the Irvine Valley and the Patna area, are assumed to be related. Xenolithic megacrysts and ultramafic nodules in many of the vent intrusions yield valuable information on the upper mantle source area of the magmas.

In the Thornhill Basin, the Carron Basalt Formation, represented by the **Carron Water** GCR site, is up to 50 m thick and rests unconformably on reddened Coal Measures and Lower Palaeozoic rocks. It comprises subaerial olivine-microphyric basalts and basanites similar to those of the Mauchline Basin and interbedded sedimentary units. Conglomeratic sandstones and breccias below the lavas, and beyond the present lava outcrop, contain angular fragments of basalt indicating earlier, possibly more extensive, flows. Although some basalts incorporate wind-blown sand in their matrix, the sedimentary rocks interbedded with and overlying the volcanic rocks are predominantly fluvial. Aeolian desert conditions did not become fully established here until well after the volcanic period. Small outliers of olivine basalt rest upon Middle Coal Measures at the south-east end of the Sanquhar Basin and five small necks pierce the Coal Measures nearby.

Across the North Channel, in a borehole at Larne in Northern Ireland, over 600 m of basic volcanic rocks were proved at a depth of over 2000 m, beneath an undoubted Permo–Triassic succession (Penn *et al.*, 1983). A K-Ar whole-rock date of 245 ± 13 Ma is almost certainly too young and the authors suggested an Early Permian age. However, there are marked petrological differences between these lavas (which have possible tholeiitic affinities) and those of south-west Scotland. They occupy a separate sedimentary basin and are certainly a separate lava field.

Offshore

In the centre of the East Irish Sea Basin, a borehole has penetrated 45.5 m of altered basalts overlain by 22 m of volcaniclastic rocks at the base of the Permian succession (Jackson *et al.*, 1995, 1997). These Tormentil Volcanics occur on a high that trends north-east towards south Cumbria, where clasts of olivine-dolerite and vesicular basalt are abundant in basal Permian conglomerates in the Humphrey Head Borehole (Adams and Wadsworth, 1993). The source of these clasts is not known, but they are likely to be Carboniferous to Early Permian in age and relatively local. Thin subaerial basaltic flows are also recorded from the Lower Permian rocks of the North Sea Basin (Dixon *et al.*, 1981).

Highlands and Islands (Early Permian)

On the Isle of Arran, the sequence at the head of the Sliddery Water that includes possible Passage Formation volcanic rocks (see above), passes up into gritty feldspathic sandstones and slaggy basaltic lavas with thin tuffs that have been assigned to the base of the Permian succession on the current British Geological Survey 1:50 000 map (1987).

A 120 m-thick Permian succession is exposed on the small island of Glas Eilean in the Sound of Islay, between the Isles of Islay and Jura (Pringle and Bailey, 1944; Upton *et al.*, 1987) (Figure 4.2). Above a basal conglomerate and sandstone (7 m thick), which contain basaltic clasts, most of the succession comprises subaerial basaltic lavas. There are many individual flows, up to 2 m thick and with slaggy amygdaloidal tops. The flow thickness decreases upwards as intercalations of shallow-water sedimentary rocks increase. The lavas are all mildly alkaline olivine-microphyric basalts that are hypersthene- or nepheline-normative and the lower flows are relatively primitive with high MgO, Ni and Cr contents. The succession appears to overlie Dalradian rocks unconformably to the ENE, and dips WSW at *c.* 30°, towards an inferred NNW-trending fault along the sound. It therefore seems to occupy a half-graben, a possible transverse extension off the northern end of the Rathlin Basin, which may have been active at the time of the sedimentation and volcanism (Fyfe *et al.*, 1993; Anderson *et al.*, 1995). A K-Ar whole-rock date of 285 ± 5 Ma appears to confirm the Early Permian age.

Evidence of more widespread Early Permian volcanism in the Highlands and Islands comes from the distribution of small sub-volcanic necks (Figure 4.4), composed largely of explosion breccia, but characterized by the presence of monchiquite, either as clasts, or as a magmatic matrix, or in associated minor intrusions (Rock, 1983). They are thus correlated petrographically with the even more widespread camptonite and monchiquite dykes swarms that are well established as being of Early Permian age (see Chapter 5; Figure 5.2). Nine necks, including that at Stob a'Ghrianain (Hartley and Leedal, 1951), seem to define a NW-trending lineament between Coire na Ba, near Kinlochleven (Wright in Bailey and Maufe, 1960) and Toscaig, near Applecross (Rock, 1982). Most others form a cluster around south-east Orkney (Mykura, 1976) which includes the neck at Duncansby Ness, dated at around 270 Ma by K-Ar whole-rock dating (Macintyre *et al.*, 1981). Like the dykes, many of the necks are a valuable source of inclusions derived from the lower crust and upper mantle (e.g. Chapman, 1975) (see Chapter 1).

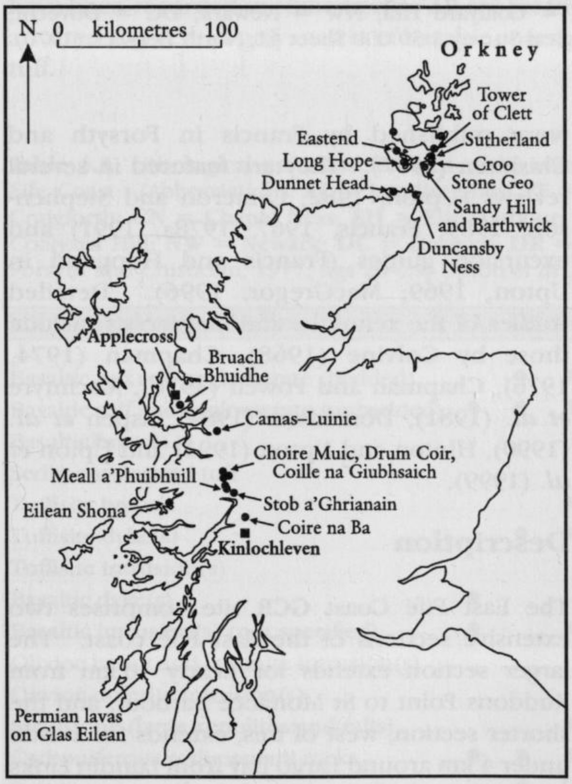

Figure 4.4 Map showing the location of plugs and vents of Carboniferous to Permian age in the Highlands. The Early Permian lavas of Glas Eilean are also indicated. After Rock (1983).

EAST FIFE COAST, FIFE (NO 408 024–NO 444 020 and NO 454 006–NO 526 015)

I.T. Williamson

Introduction

The coastal section between Lundin Links and St Monance in the East Neuk of Fife, which comprises the East Fife Coast GCR site, includes numerous volcanic necks (Figure 4.5). Excellent exposures and a wide variety of volcanic features within a relatively small area make this a valuable site for both research and educational purposes. It is well known internationally, regularly visited by field parties, and is much cited in scientific literature.

In many instances the three-dimensional relationships within the necks and between necks and country rock are clearly seen. Associated strata include bedded and massive, pyroclastic and volcaniclastic deposits; all are cut by minor intrusions and a few necks have a central intrusive plug. The volcanism was commonly phreatic or phreatomagmatic, reflecting the interaction of magma with water, and there are many examples of localized magma–sediment interaction.

In East Fife in general there are more than 100 known volcanic necks, which cut Carboniferous strata ranging from the Pathhead Formation (top Visean) to Middle Coal Measures (Westphalian B). Radiometric ages on associated intrusions span the Late Carboniferous (Stephanian)–Permian boundary, but some may be contemporaneous with earlier volcanic beds in the local Namurian to Westphalian succession. Some necks are associated with the Ardross Fault, an important ENE-trending strike-slip structure that extends for about 8 km, more-or-less axial to the Midland Valley. It possibly exerted control on

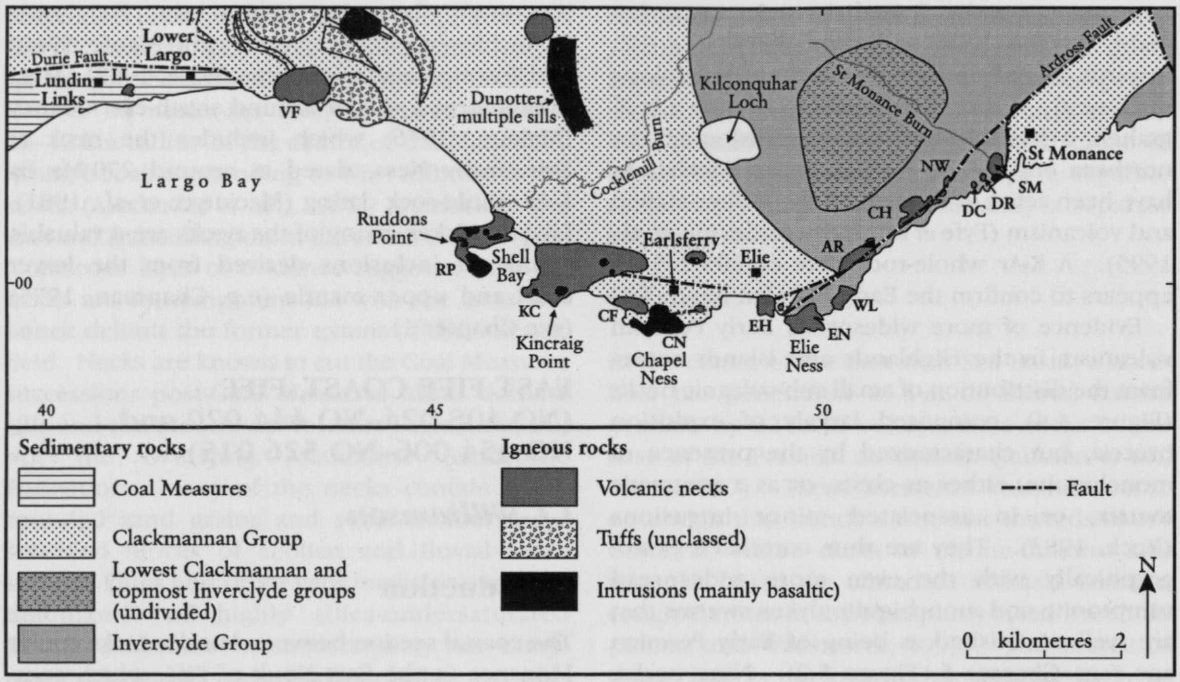

Figure 4.5 Map of the south-east Fife coast, showing the distribution of volcanic necks. The named volcanic necks lie within the East Fife Coast GCR site. (Volcanic necks, from west to east: LL = Lundin Links; VF = Viewforth; RP = Ruddons Point; KC = Kincraig; CF = Craigforth; CN = Chapel Ness; EH = Elie Harbour; EN = Elie Ness; WL = Wadeslea; AR = Ardross; CH = Coalyard Hill; NW = Newark; DC = Dovecot; DR = Davie's Rock; SM = St Monance.) Based on Geological Survey 1:50 000 Sheet 41, North Berwick (1970).

the location of the volcanism and is thought to be a re-activated Caledonian basement structure.

Both fragmental and crystalline intrusive rocks in a number of the necks contain xenoliths and megacrysts of lower-crustal and upper-mantle material. Their study has provided a major contribution to knowledge of the deep structure of northern Britain and has given an insight into the genesis of the Carboniferous–Permian magmas (see Chapter 1). They have also provided a source of material for numerous detailed studies of individual minerals such as garnets and zircons.

The necks have long attracted the attention of geologists and were first described by Geikie (1880, 1897, 1902) and Wallace (1916). Important work was done by Balsillie (1920a,b, 1923, 1927) and Cumming (1928, 1936), but it is mainly the detailed work of E.H. Francis to which we owe most of our present knowledge (Francis, 1960, 1968a,b, 1970b; Francis and Hopgood, 1970). Comprehensive details of the field relationships of the necks and their interpretation in terms of Silesian volcanic processes were published by Francis in Forsyth and Chisholm (1977). They are featured in several reviews (Upton, 1982; Cameron and Stephenson, 1985; Francis, 1967, 1978a, 1991) and excursion guides (Francis and Hopgood in Upton, 1969; MacGregor, 1996). Detailed studies of the xenoliths and megacrysts include those by Colvine (1968), Chapman (1974, 1976), Chapman and Powell (1976), Macintyre *et al.* (1981), Donaldson (1984), Aspen *et al.* (1990), Hinton and Upton (1991) and Upton *et al.* (1999).

Description

The East Fife Coast GCR site comprises two extensive sections of the East Fife coast. The larger section extends for nearly 10 km from Ruddons Point to St Monance harbour, and the shorter section, west of this, extends for a little under 4 km around Largo Bay from Lundin Links to Viewforth. Of additional geological interest at the site are the local sedimentary sequence, fish and amphibian fossils (Dineley and Metcalfe, 1999), raised beaches, and mineral localities.

A total of 15 or so volcanic necks with associated plugs and minor intrusions, crop out within the site. Most are well exposed in the intertidal zone though exposures vary from time to time. The field relationships of individual necks are described in great detail by Francis (in Forsyth and Chisholm, 1977) and a summary of their main lithological units and structural features is shown here in Table 4.1. The original relationships of these lithologies and structures within the original volcanoes may be conveniently illustrated in a hypothetical cross-section (Figure 4.6).

Lithological components of the necks

Pyroclastic rocks form the principal component of all the necks. The dominant clasts are grey to greenish-grey alkali basalt and basanite, which vary in size from coarse ash to lapilli with rare larger bombs. They are predominantly of the ragged-edged, chilled juvenile type but there are also accessory lapilli and blocks. Other clasts are massive or thinly bedded tuffs and sedimentary rock debris. Fragments of woody material have been recorded in some necks. All are set in an altered greenish-grey matrix of basaltic coarse tuff.

Bedded tuffs appear to be more common than massive tuffs, but the two are intimately associated in the necks and commonly pass laterally into one another. The bedded tuffs are usually medium to thickly bedded and individual beds are moderately sorted. Sedimentary structures include graded bedding and cross-bedding. The massive tuffs are considerably more heterogeneous. They may be either moderately sorted or unsorted and chaotic. The less well-sorted tuffs generally occur towards the centre of necks.

Pyroclastic breccias in which the clasts are predominantly angular and almost exclusively of basalt, are commonly located in the more central portions of the necks. In some cases they grade into marginal basalt-dominated bedded tuff and agglomerate or into coherent basaltic intrusions.

Sediment-derived tuffs are most commonly located at the margins of a neck. Here they either grade outwards into country rock or are bound on both sides by ring-fractures. These tuffs are grey to greenish in colour and are composed mostly of fragments of brecciated country rock, most commonly sandstone, ranging in size up to blocks. In addition, there may be a small but variable population of basaltic clasts and

Table 4.1 Lithological units and features of the volcanic necks between Lundin Links and St Monance, East Fife Coast. (Abbreviations: **LL** = Lundin Links; **VF** = Viewforth; **RP** = Ruddons Point; **KC** = Kincraig; **CF** = Craigforth; **CN** = Chapel Ness; **EH** = Elie Harbour; **EN** = Elie Ness; **WL** = Wadeslea; **AR** = Ardross; **CH** = Coalyard Hill; **NW** = Newark; **DC** = Dovecot; **DR** = Davie's Rock; **SM** = St Monance.) Based on Francis in Forsyth and Chisholm, 1977, figs 20–24; Upton *et al.*, 1999.

Lithological units / Necks	LL	VF	RP	KC	CF	CN	EH	EN	WL	AR	CH	NW	DC	DR	SM
Basaltic tuff and agglomerate (bedded)		●	●	●	●		●	●	●	●		●			●
Basaltic tuff and agglomerate (unbedded)	●	●	●	●				●	●	●	●	●	●		●
Basaltic breccia				●			●								
Sediment-derived tuff					●					●	●	●			
Tuffisite breccia			●	●	●	●	●		●	●			●	●	●
Tuffisite dyke(s)		●	●	●		●		●					●		●
Tuffisite intrusion(s)									●	●		●	●		
Basaltic dyke(s)	●				●		●	●	●	●			●		
Basaltic intrusion(s) (not specified)	●		●	●							●			●	●
Olivine basalt and basanite intrusion(s)						●	●							●	
Olivine-dolerite intrusion(s)							●	●							
Sandstone (large xenoliths and rafts)			●	●			●			●	●		●		●
Carboniferous sedimentary rocks	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Bedding: ●=collapsed;○=centroclinal		●	○	●	○		○	●○	○						
Marginal ring-faults or shear zones	●	●		●			●				●				●
Cryptovolcanic structures				●	●								●		
Megacrysts and xenoliths			●					●		●	●				

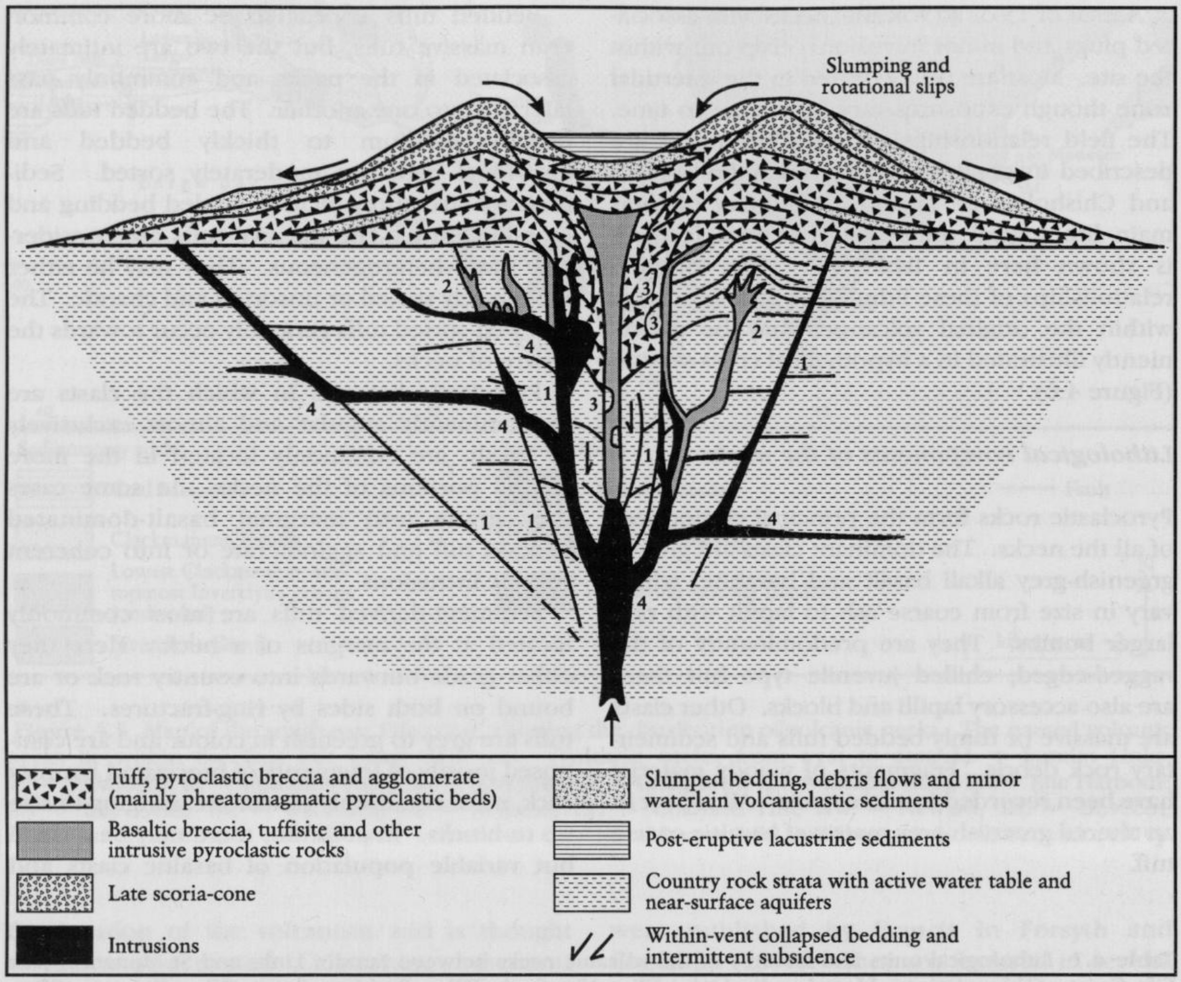

Figure 4.6 Schematic cross-section through an evolving tuff-ring, illustrating some of the volcanic processes thought to have been involved in the emplacement of the East Fife volcanic necks. The exposed necks within the GCR site may be interpreted in terms of sub-horizontal sections through this structure. (Features marked on the diagram: 1 = ring-faults with marginal tuffisite and breccia, or basaltic dykes; 2 = tuffisite within country rock – may develop adjacent to sills or dykes; 3 = large foundered bodies of country rock within vent and entrained within breccias and tuffisite; 4 = minor intrusions emplaced along bedding and fault planes.) Based on Forsyth and Chisholm (1977, fig. 17 after Francis, 1970b and Lorenz, 1973); Lorenz (1986); and Godchaux *et al.* (1992).

even some basaltic bombs; examples of the latter are seen in the Craigforth Neck. The matrix is generally also derived from the country rock and comprises comminuted lithic fragments and crystals.

Tuffisites (intrusive tuffs) were emplaced along radial and concentric fractures within most of the East Fife necks and they are common on the inside of marginal ring-fractures. They also occur as a marginal facies to associated basaltic intrusions. A characteristic feature is a strong flow foliation, especially at the margins. When derived from a mainly sedimentary source, tuffisite commonly veins or acts as the matrix to many of the breccias and sediment-derived tuffs associated with the volcanic necks.

Minor intrusions of basalt, basanite and dolerite are commonplace in and near the volcanic necks. Many are highly irregular. They range from minor dykes and sheets, commonly occupying ring-faults or radial fractures, to central plug-like bodies. The larger intrusions exhibit columnar jointing, indicating slow and uninterrupted cooling. Some basaltic dykes intruding the adjacent, locally carbonaceous, country rock are extremely altered. Their very pale and bleached appearance is due to replacement by carbonates and the rock-type is traditionally referred to as 'white trap'.

Structural features of the necks

Most of the necks have an irregular, but broadly oval, plan and vary in size from a few tens of metres to hundreds of metres across. Their margins are usually inwardly dipping and are commonly ring-faults.

Within the tuff and agglomerate of many necks, there are small areas, usually ill-defined, where the attitude of the bedding and of large rafts of fractured bedded tuff, has been disturbed, re-orientated and even overturned. Some beds appear to have flowed or deformed plastically. Where bedding is relatively undisturbed it is centroclinal, i.e. inclined inwards towards a central focus, with the higher dips close to the neck margins.

Cryptovolcanic ring-structures are noted sporadically among the country rocks near some necks. These are circular or oval areas of variably brecciated strata that vary considerably in size from 3 m to 200 m in diameter. The breccias are composed entirely of angular clasts of sedimentary rock up to several metres across in a variable amount of matrix that consists of tuffisite of mainly sedimentary origin. The degree of fragmentation varies from simply fractured in the smaller structures, through in-situ breccias with increasingly disorientated clasts, to coarse breccias with a higher proportion of matrix and veins of tuffisite in the larger structures. Thin dykes of bleached basalt feature in some. The structures range from small swells and gentle domes to larger vertically sided ring-structures in which blocks become orientated parallel to the contacts.

The individual necks

The necks may be conveniently divided into those associated with the Ardross Fault and those that are not.

Only the necks in the eastern half of the GCR site are associated with the Ardross Fault. They are the Elie Harbour Neck (NO 4930 9955), Elie Ness Neck (NO 498 994), Wadeslea Neck (NO 503 997), Ardross Neck (NO 5045 0020), Coalyard Hill Neck (NO 5120 0085), Newark Neck (NO 516 012), Dovecot Neck (NO 5095 0115), Davie's Rock Neck (NO 5210 0125) and St Monance Neck (NO 5225 0140). The last three are situated south-east of the Ardross Fault but are still loosely aligned along its trend.

The *Elie Harbour Neck* consists of tuffs, lapillistones and agglomerate, traversed by a few impersistent basaltic dykes. The agglomerate consists of large blocks and bombs of scoriaceous basalt and sedimentary rock, including, in the central part of the neck, a large raft of sediment-derived tuffisite. Geikie (1902) also noted fragments of wood and coal. The Ardross Fault separates the Elie Harbour Neck from the *Elie Ness Neck*. The latter, orientated crudely north-east–south-west, comprises well-bedded, inward-dipping (centroclinal) basaltic tuffs and agglomerates. Sedimentary structures include cross-bedding, graded bedding and slump-bedding, and deformation caused by the impact of volcanic ejecta and contemporaneous collapse (Figure 4.7). The pyroclastic rocks also contain 'breadcrust' bombs of basalt and blocks of sedimentary rock, but it is for its exotic clasts that the neck is perhaps best known. These include various xenolithic nodules and xenocrysts. The latter include pyrope garnet (so-called 'Elie Ruby'), zircon and alkali feldspars. The Elie Ness Neck is separated from the *Wadeslea Neck* by a narrow outcrop of folded sedimentary rocks, and minor tuffisite breccia. The *Ardross Neck*, on the opposite side of the Ardross Fault to the Wadeslea Neck, is comparatively simple and comprises only massive and bedded tuff and agglomerate. A series of *en échelon* dykes of xenolithic basalt, penetrated locally by sediment-derived tuffisites, is present in the northern part. Divorced from the main body of the Ardross Neck, but situated a short distance to the north-east along the line of the Ardross Fault, are two small outcrops of tuffisite. These are important because their orientation, and also that of the materials within them, mirrors that of the fault, strongly suggesting that their emplacement had strong tectonic control.

The *Coalyard Hill Neck* is described by Francis (in Forsyth and Chisholm, 1977) as a composite structure, consisting of outer and inner necks. These are very different in form and lithology, but collectively they demonstrate the structure and evolution of a typical Late Carboniferous Midland Valley volcanic neck. The outer neck, which is the older, is only 100 m wide but extends for about 700 m along the north-western side of the Ardross Fault. It is dominated by sediment-derived tuff but there is scattered basaltic material within it. It is cut by tuffisite veins, and flow-banded tuffisite commonly flanks the larger clasts and rafts (Figure 4.8), including some large blocks of crinoidal limestone at the western margin. The inner neck consists of

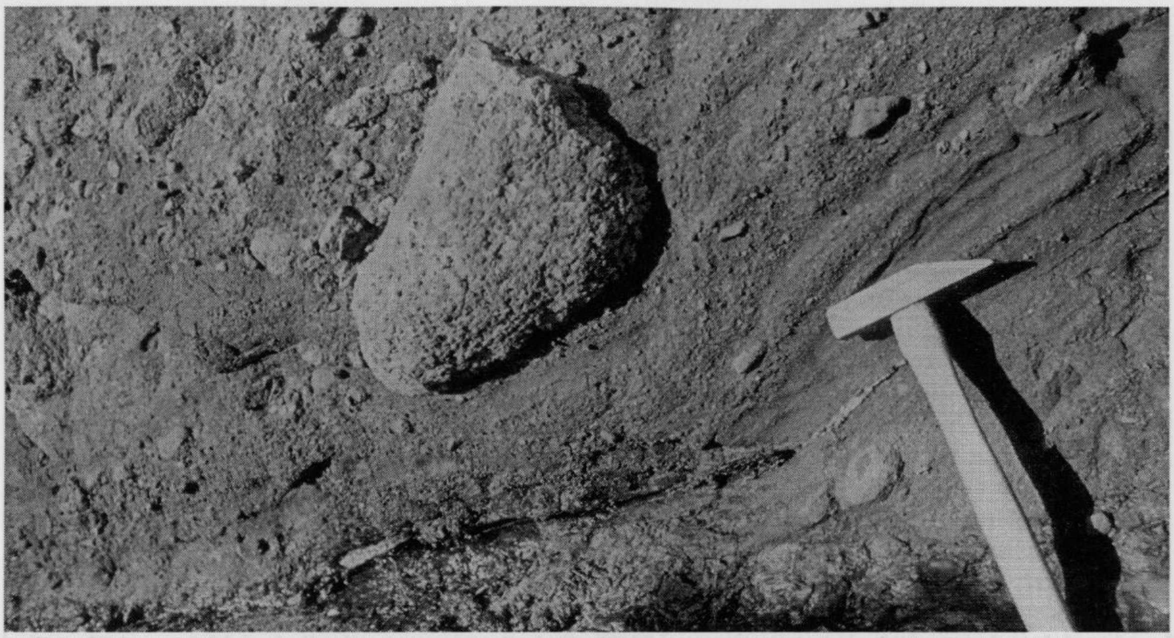

Figure 4.7 Basaltic bomb showing impact effects in the underlying tuffs, Elie Ness Neck, East Fife Coast GCR site. The hammer head is about 15 cm long. (Photo: British Geological Survey, No. MNS1635, reproduced with the permission of the Director, British Geological Survey, © NERC.)

Figure 4.8 Flow-banding in tuffisite (below hammer) intruded into a large raft of sandstone (on which the hammer rests) in the north-eastern part of the Coalyard Hill Neck, East Fife Coast GCR site. The pale fragments elongated parallel to the edge of the sandstone are of bleached basalt. The hammer shaft is about 35 cm long. (Photo: British Geological Survey, No. D1680, reproduced with the permission of the Director, British Geological Survey, © NERC.)

massive, basaltic tuffs and agglomerates with ill-defined masses of basaltic breccia and minor basaltic intrusions. A small intrusion of basanite at the south-western contact contains xenoliths of spinel lherzolite and also rare wehrlite and pyroxenite (Table 4.2). Only a small area of the *Newark Neck* is exposed on the north-western side of the Ardross Fault. It mainly comprises sediment-derived tuffs although locally the matrix carries fragments of juvenile basalt. These tuffs grade imperceptibly into bedded basaltic tuffs and agglomerates forming the central zone of the neck.

The small *Dovecot Neck* provides good examples of neck-margin phenomena such as the localized thrusting, deformation and induration of country rock and intrusions of flow-aligned tuffisite. One large raft of sandstone, penetrated from below by flow-aligned tuffisite, may have formed part of the stoped roof of a cryptovolcanic ring-structure. The *Davie's Rock Neck* is emplaced in the crest of an anticline and consists of a central plug-like mass of nepheline basanite surrounded by tuffisitic breccia. Francis interpreted the exposures as a deep section through another large cryptovolcanic structure. The *St Monance Neck* is the most easterly neck in the GCR site. It consists almost entirely of massive, unbedded lapilli-tuff and agglomerate cut by a series of cross-cutting monchiquitic dykes (Figure 4.9). Large clasts of sedimentary rock, some with tuffisite veining, are common towards the margins.

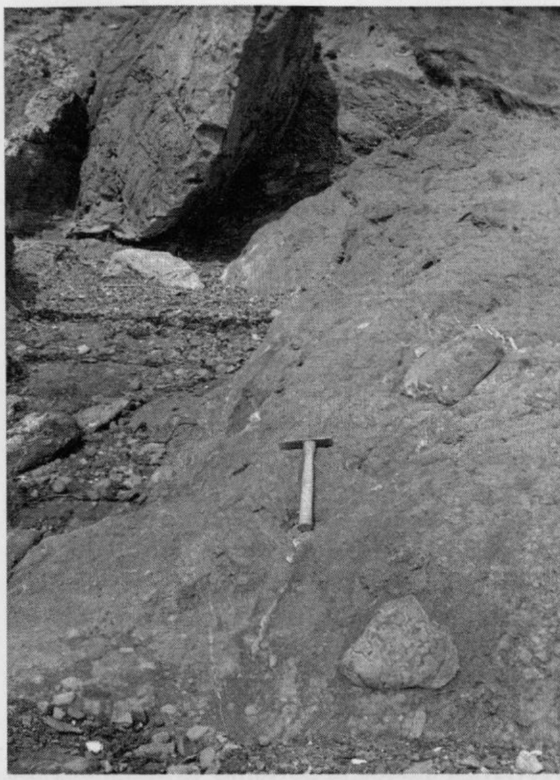

Figure 4.9 Western margin of the St Monance Neck, East Fife Coast GCR site, showing tuff and agglomerate (right), upturned, disorientated sediments (top left) and a monchiquitic dyke emplaced along part of the margin (top centre). The hammer shaft is about 35 cm long. (Photo: British Geological Survey, No. D1679, reproduced with the permission of the Director, British Geological Survey, © NERC.)

Table 4.2 Distribution of accidental xenoliths and megacrysts in the East Fife necks (* = fragmental pyrope garnets – the famous, so-called 'Elie Ruby') (additional minor xenocryst phases are listed in the text). (Abbreviations: **RP** = Ruddons Point; **EN** = Elie Ness; **CH** = Coalyard Hill; **AR** = Ardross.)

Volcanic Neck	RP	EN	CH	AR
Xenoliths				
Hydrated ultramafic rock		•		•
Spinel lherzolite	•		•	
Wehrlite	•		•	
Biotite-amphibole pyroxenite	•		•	
Anorthoclasite	•	•		
Pyroxene granofels and gneiss	•			
Quartzo-feldspathic granofels and gneiss		•		
Garnetiferous quartzo-feldspathic granofels and gneiss			•	
Garnetiferous ultramafic rock		•		
Principal megacrysts and xenocrysts				
High-temperature feldspar – mainly anorthoclase	•	•	•	•
Garnet *		•		
Corundum	•			
Zircon		•		

Necks that are not associated with the Ardross Fault are all situated north-west of the fault. They are the Lundin Links Neck (NO 411 024), Viewforth Neck (NO 431 024), Ruddons Point Neck (NO 454 004), Kincraig Neck (NO 466 998), Craigforth Neck (NO 475 996) and Chapel Ness Neck (NO 4755 9935).

The *Lundin Links Neck* is the most westerly within the GCR site. It is comparatively small and cuts the Middle Coal Measures some 30 m below the Barncraig Coal. The *Viewforth Neck*, farther east around Largo Bay, is composed solely of fragmental deposits. It has steeply dipping, inwardly inclined margins against Passage Formation strata. The *Ruddons Point Neck* forms a rocky promontory between Largo Bay and Shell Bay and is formed of approximately equal proportions of pyroclastic rocks and basaltic intrusions. The main plug is one of the largest in East Fife. The intrusions carry xenocrysts (Table 4.2). On the opposite side of Shell Bay the *Kincraig Neck*, measuring 1.5 km in length, is the largest of the coastal necks in East Fife. It contains most of the elements and features listed in Figure 4.6 and provides a unique opportunity to determine the three-dimensional relationships between neck materials, intrusions and country rock. The largest intrusion is a flat-based boss or sill-like body of basalt with exceptionally well-developed columnar jointing (Figure 4.10). Both the *Craigforth Neck* and the *Chapel Ness Neck* are comparatively small structures. The latter is unusual in that it mainly comprises an irregular-shaped intrusion of olivine basalt and basanite. Elie Bay to the east contains at least three cryptovolcanic ring-structures.

The Ardross Fault

The surface trace of the Ardross Fault is most readily seen in the shore sections between the Elie Ness, Wadeslea, Ardross and Coalyard Hill necks. The line of the fault is traceable by lithological contrasts on either side, and locally by an ill-defined weathered-in zone. The style of the folding in the adjacent country rock is broad and open on one side, and tight, locally isoclinal, on the other; the intensity of folding dies out abruptly away from the fault. The fault shows dextral lateral movement and there is a consistent sense of vertical drag with a downthrow to the north-west (Francis and Hopgood, 1970). Although the fault appears to control the siting of many of the necks, the principal fault movements demonstrably post-date neck emplacement.

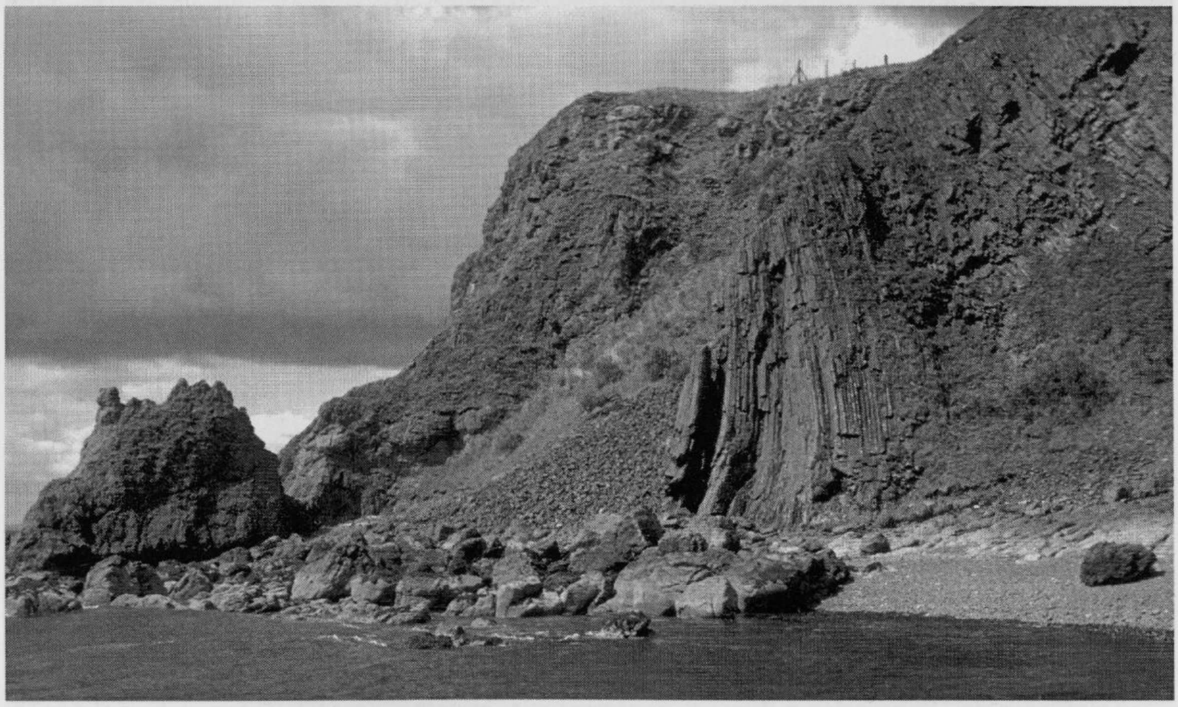

Figure 4.10 Curved columnar jointing in basalt intrusion within the Kincraig Neck, East Fife Coast GCR site. (Photo: British Geological Survey, No. D1684, reproduced with the permission of the Director, British Geological Survey, © NERC.)

The xenolith, cumulate inclusion and megacryst suites

In addition to the dominant clasts of juvenile or 'parental' basaltic material, some tuffs and intrusions in the necks contain sparse, more exotic clasts such as large, accidental crystals and various mafic and ultramafic rocks. Similar material also occurs as megacrysts and xenoliths in associated intrusions (Table 4.2). The Ruddons Point, Elie Ness, Ardross and Coalyard Hill necks are internationally famous in this respect, and this extremely important feature of the Carboniferous–Permian Igneous Province of northern Britain is discussed more fully in Chapter 1.

The majority of exotic inclusions and xenoliths in the Elie Ness and Ardross necks are hydrated ultramafic rocks (Chapman, 1976), including both feldspar-free and albite-bearing pyroxenites. In the Ruddons Point and Coalyard Hill necks the commonest type is a spinel lherzolite but there are also scarce iron-rich wehrlites as well as biotite- and amphibole-rich pyroxenites, rare composite wehrlite–lherzolites, websterites and garnet-bearing pyroxenites (Chapman, 1974). Other rock-types include metamorphic rocks such as granulite-facies mafic gneisses and both garnetiferous and quartzo-feldspathic gneisses. Examples of the latter, with plagioclase porphyroblasts, are recorded from the Coalyard Hill Neck.

Anorthoclase, a high temperature alkali feldspar, is the commonest megacryst phase in the Fife necks (Chapman and Powell, 1976; Aspen *et al.*, 1990). Pinkish-white crystals, some over 10 cm in size, have been found in most necks. Anorthoclase-dominated composite megacrysts grade into anorthoclasites with subordinate zircon, chlorite pseudomorphs after clinopyroxene, corundum and an yttro-niobate rich in the heavy rare-earth elements uranium and thorium (Upton *et al.*, 1999). The Ruddons Point Neck contains the broadest compositional range of anorthoclase megacrysts, with lesser ranges in the Elie Ness, Coalyard Hill and Ardross necks. The Elie Ness Neck is noted for its fresh, orange-brown, fractured, but inclusion-free, pyrope garnets (Colvine, 1968; Donaldson, 1984). They are known locally as 'Elie Rubies' and occur mostly as fragments from 0.25 mm to 25 mm in size. Sub-calcic augite, kaersutite, magnetite, apatite and zircon (the latter rarely up to up to 5 mm in size) have also been recorded at Elie Ness. Orthopyroxene has been recorded at Ruddons Point (Balsillie, 1927), Davie's Rock and Coalyard Hill.

Timing of volcanic activity

The age of the East Fife necks has been the subject of considerable debate. Country rocks range from Dinantian (Asbian–Brigantian) Pathhead Formation strata at, and east of, the Elie Ness Neck, to (Westphalian B: Duckmantian) Middle Coal Measures strata at the Lundin Links Neck. Tuffs interbedded with the local sedimentary succession demonstrate that East Fife had an almost unbroken history of volcanic activity from early Namurian to mid-Westphalian times, so it is possible and indeed likely that the necks span a similar range.

K-Ar whole-rock ages of intrusions within East Fife necks (Forsyth and Chisholm, 1977; Forsyth and Rundle, 1978) show a range from Stephanian to Early Triassic. The youngest (244 ± 6 Ma), was obtained from a minor intrusion within the Lundin Links Neck but is perhaps anomalous due to argon loss. However, the five oldest results, from St Monance, Chapel Ness, Davie's Rock and Largo Law, are indistinguishable within the limits of analytical error within the range 295–288 Ma and hence the best estimate for the time of emplacement is close to the Stephanian–Permian boundary (Forsyth and Rundle, 1978; Wallis, 1989). Other K-Ar whole-rock dates for intrusions from Kincraig (De Souza, 1979) and from the Ruddons Point, Kincraig and Chapel Ness necks by Wallis (1989) all seem to be anomalously young.

K-Ar dating of both inclusions and intrusions associated with the Ruddons Point, Kincraig, Elie Harbour, Elie Ness, Ardross and Coalyard Hill necks was carried out by Macintyre *et al.* (1981). The results suggest that basanites in both of the Elie necks have a probable minimum emplacement age of 276 ± 4 Ma (Early Permian). Anorthoclase megacrysts from the Ruddons Point, Elie Ness, Ardross and Coalyard Hill necks appear to have crystallized by 294 ± 3 Ma (Stephanian). However dating of ultramafic cumulate xenoliths from the Elie Ness and Kincraig necks suggests that the inclusions formed or last equilibrated much earlier, at 315 Ma (Namurian to Westphalian boundary) and at shallow depth. Similar ages have been obtained from megacrysts at Elie Ness; around 318 Ma by U-Pb on zircons (Macintyre *et al.*, 1981) and a plateau age of 311 ± 3 Ma by Ar-Ar on kaersutite (M. Timmerman, pers. comm., 2002).

Interpretation

The location of several volcanic necks within the East Fife Coast GCR site appears to have been controlled by the Ardross Fault. This high-level fault probably resulted from the re-activation of a deep-seated Caledonian structure and is considered to have been active intermittently throughout the Carboniferous and perhaps into the Permian Period (Francis and Hopgood, 1970). The radiometric ages of the necks suggest that they were probably emplaced during Stephanian to Early Permian times. During this time shallow-water environments persisted (Forsyth and Chisholm, 1977) and this had a pronounced effect upon the style of the contemporaneous volcanism.

The present-day outcrop of each neck represents a horizontal slice through the sub-volcanic plumbing of a small- to medium-sized volcano. These volcanoes were the result of violent eruptions and produced mainly fragmental pyroclastic products rather than lavas. There is considerable evidence to suggest that many of these eruptions were steam-driven phreatic and phreatomagmatic explosions, as bodies of ascending magma came into contact with aquifers, wet sediments or bodies of standing water such as shallow seas and lakes. The ash cones that typically form in such conditions have a wide diameter and relatively low height and are termed tuff-rings or maars (Lorenz, 1973, 1986). This type of activity is often compared to Surtseyan-style volcanism of marine areas, as summarized by Kokelaar (1986) and White and Houghton (2000). Phreatomagmatic volcanoes in general range from subaqueous to emergent to subaerial (Godchaux *et al.*, 1992), but the Fife volcanoes most readily fit the transition from emergent to subaerial.

Much of the form and structure of the volcanoes has been preserved due to post-eruptive processes, especially the foundering of sequences within the funnel-shaped conduits that now constitute the necks. Areas of collapsed and centroclinal bedding are thought to be due to the intermittent and progressive inward collapse of unconsolidated fragmental deposits as the magma withdrew to depth. The dominant centroclinal bedding in any one neck is related to the final stages of collapse, generally at the end of the last episode of volcanic activity at that site. The margins of many necks are ring-fractures and it is thought that some of the Fife volcanic sequences may have subsided by up to 500 m, revealing a variety of original structural levels at current erosion levels. However, ring-fracturing may have been an intermittent phenomenon with several generations of subsidence (Lorenz, 1973, 1986; Francis, 1991). The intermittent nature of the volcanicity is indicated by the abundance within the necks of obviously recycled clasts, such as blocks of bedded tuff and volcaniclastic breccia.

The necks are filled by pyroclastic and volcaniclastic rocks that formed sequences of volcanic ejecta in and around the volcanic craters. The presence of bedding, along with fragments of wood, volcanic bombs and clasts of contemporary sedimentary origin, some with interbedded coals, all strongly imply a mainly subaerial origin. The basal facies of subaerial volcanoes such as these usually contain much non-juvenile, country-rock material, commonly as large blocks. Such lithologies are well represented in most of the East Fife necks. Beds of massive tuff within otherwise bedded sequences may be high-concentration base-surge deposits (Chough and Sohn, 1990). Base-surge activity may also have formed some of the hummocky cross-bedding. Other cross-bedding may be due to reworking with the development of slump or debris sheets and lahar-like slurries.

Tuff sequences that are unbedded or with only minor bedded units suggest a more sub-aqueous origin. This is a common feature in the basal facies of small phreatic to phreatomagmatic volcanoes (Godchaux *et al.*, 1992), where initial activity is accompanied by chaotic deposits and some mobilization, often resulting in slumps and debris flows. The highly degraded state and green colouration of many of the basaltic clasts may reflect the formation of basaltic glass due to quenching by the water, followed by rapid alteration to palagonite and subsequently to chloritic residues. Since there are no known pillow lavas and associated hyaloclastite breccias in the Fife necks at their present levels of exposure, this subaqueous phase was probably short-lived. The phreatomagmatic phase was probably followed by more dominantly magmatic activity in which basaltic pyroclastic eruptions occurred subaerially or in shallow water.

The cryptovolcanic ring-structures are believed to represent incipient neck formation, the breccias forming in country-rock strata above magma bodies that failed to breach the surface to form volcanic cones. Where this explosive brecciation of both country rock and contemporaneous volcanic products was followed by their mobilization through gas/steam fluidization or fluxion processes, bodies of tuffisite were emplaced.

Magmas failing to reach the surface were emplaced as sub-surface intrusions. Most were intruded as dykes, thin sheets and irregular masses, but some formed solid plug-like structures to the main volcanic vents. The Ruddons Point intrusion, for example, is one of the largest in East Fife. The basaltic breccias that are common in the central parts of the necks may be interpreted as either pyroclastic breccias or as masses of intrusive basalt brecciated *in situ* by subsequent intrusions and violent gas and stream-driven eruptions. There is no conclusive proof of subaerial lavas having developed, though these might have been a natural consequence of the later evolution of the volcanoes. Some dykes and plugs may have fed lavas, though no direct evidence for this exists.

The 'exotic' inclusions, xenoliths and megacrysts that occur within the necks and associated intrusions are thought to have been derived from the lower crust and the lithospheric upper mantle. Assemblages from several of the East Fife necks (Table 4.2) have played a leading part in formulating ideas as to the deep structure of the Midland Valley (e.g. Upton *et al.*, 1984) and also in the construction of complex petrogenetic models (e.g. Macintyre *et al.*, 1981; Upton *et al.*, 1999) (see Chapter 1). Chapman (1976) interpreted the various igneous xenoliths from the Elie Ness Neck as within-mantle and within-crust differentiates of alkali basalt magmas. Studies of the pyrope garnet megacrysts ('Elie Rubies') by Colvine (1968) and Donaldson (1984) suggest that the magmas contained significant water and were cooler than had been supposed previously. Aspen *et al.* (1990) considered that the anorthoclase megacrysts represent syenitic (salic alkaline) vein deposits crystallized from magmas in the upper mantle, and Upton *et al.* (1999) concluded that they and the associated anorthoclasites may also occur as pegmatitic veins traversing pyroxenitic wall-rocks.

Conclusions

The East Fife Coast GCR site contains no less than 15 volcanic necks, the eroded remains of a series of small Late Carboniferous to Early Permian volcanoes. These exceptional exposures are of international value as they enable reconstructions of the original form of the volcanoes, their mechanisms of emplacement and the environments in which they formed. Exposure is excellent and, as the necks are exposed at different structural levels, three-dimensional relationships are clear. The site is consequently much used for research, and is a popular venue for educational field parties.

The necks are thought to represent the roots of low cinder and ash cones known as tuff-rings or maars, formed during violent (phreatomagmatic) eruptions due to the explosive interaction of magma with ground-water and surface water. The presence of intrusive fragmental rocks (tuffisites) containing much country-rock material, points to the importance of gas-streaming by water vapour generated during the eruptions. Adjacent sedimentary country rocks are commonly disrupted by folding and brecciation. Although there is no evidence that magma was ever erupted as lava, many of the necks contain minor intrusions and larger plugs of basalt, representing magma that solidified relatively close to the surface.

Some of the necks are aligned along the Ardross Fault which, although demonstrably active during and after the volcanism, is thought to be a re-activation of a deeper Caledonian basement structure and probably acted as one of a number of factors controlling the sites of the volcanoes.

Several of the necks contain suites of rocks and crystals (xenoliths and xenocrysts) brought up from great depths by the rising magmas. By studying these assemblages it is possible to investigate the high-pressure–high-temperature processes that operated beneath the volcanoes, in the lower part of the Earth's crust and the underlying upper mantle beneath the Midland Valley. The results have an important bearing upon the origin of the magmas that produced the Carboniferous–Permian Igneous Province of northern Britain.

HOWFORD BRIDGE, EAST AYRSHIRE (NS 512 254–NS 516 255)

I.T. Williamson

Introduction

The River Ayr at Howford Bridge, 1 km west of Catrine, East Ayrshire, affords a representative section through some of the youngest volcanic rocks in the Carboniferous–Permian Igneous Province of northern Britain (Figure 4.11). The lavas and tuffs of this GCR site form part of the Mauchline Volcanic Formation, which comprises the lower part of the Permian succession in the Mauchline Basin. The upper part comprises continental red bed sandstones of the Mauchline Sandstone Formation and the whole succession is 610 m thick at its maximum.

The Mauchline Basin has a simple form in which the more resistant, volcanic rocks form a low ridge surrounding a broad, shallow topographical depression. The volcanic rocks thicken eastwards from 100 m to 238 m and are probably part of a more extensive volcanic field that extended originally to the south-east, across the Southern Upland Fault, to include the Carron Basalt Formation of the Sanquhar and Thornhill basins (see **Carron Water** GCR site report).

Regionally, the Mauchline Volcanic Formation rests unconformably, but with no marked discordance, upon reddened Upper Coal Measures sedimentary rocks. Fossil plant remains from intercalated sedimentary beds elsewhere in the basin suggest an earliest Permian age (Wagner, 1983), and hence the volcanic rocks have considerable potential importance for dating the Carboniferous–Permian boundary. K-Ar whole-rock dates of around 286 ± 7 Ma were obtained from the lavas by De Souza (1979, 1982), and Wallis (1989) reported a K-Ar date of 291 ± 6 Ma from an associated neck intrusion. Palaeomagnetic measurements support an age of emplacement close to the Carboniferous–Permian boundary (Du Bois, 1957; Harcombe-Smee *et al.*, 1996).

The section was first described by Geikie (1866) (his Ballochmyle section) and subsequently by Eyles *et al.* (1949) in the Geological Survey memoir and by Mykura (1967). Excursion guides for the Glasgow district have included this key section (e.g. Weedon and Mykura in Lawson and Weedon, 1992). Detailed

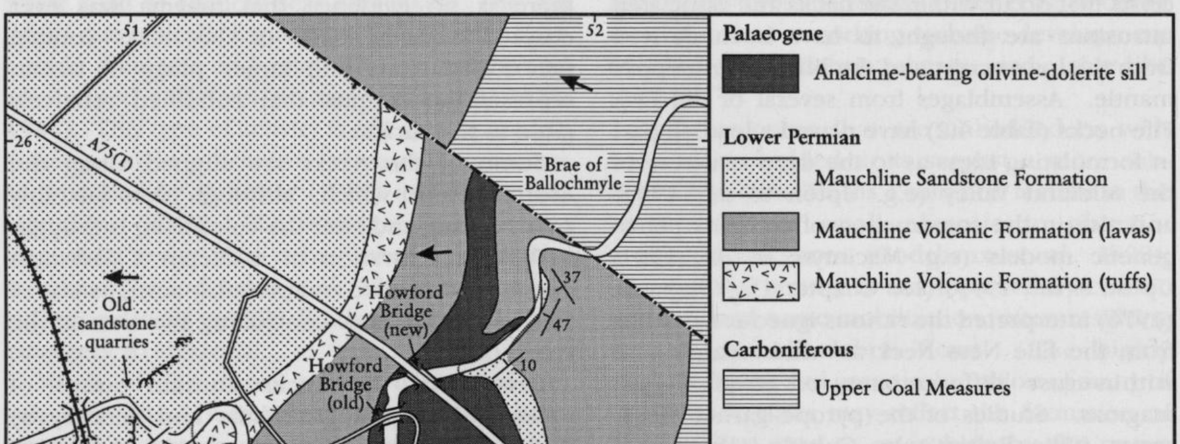

Figure 4.11 Map of the area around the Howford Bridge GCR site. Based on Geological Survey 1:10 560 sheets NS 52 NW (1966); and NS 52 SW (1964).

petrographical descriptions of the formation were given by Tyrrell (1928a), and analyses of the lavas were included in studies of Silesian and Permian magmatism of northern Britain by Macdonald *et al.* (1977) and Wallis (1989). A stream-sediment survey of the Mauchline Basin has revealed significant amounts of gold, possibly derived from the volcanic rocks and precipitated from hydrothermal solutions in the red beds (Leake *et al.*, 1997).

Description

The Mauchline Volcanic Formation is extremely variable in lithology, but comprises mainly lenticular basic lavas, with intercalated beds of tuff, tuff-breccia, agglomerate, aeolian sandstone and mudstone. The lavas are mainly olivine-microphyric and olivine-clinopyroxene-microphyric basalts with some nepheline basanites, analcime basanites and olivine nephelinites (Eyles *et al.*, 1949), though whole-rock analyses reveal many basaltic hawaiites and hawaiites (Wallis, 1989). There is a variable, localized basal unit of tuffs and volcaniclastic sandstones. The overlying Mauchline Sandstone Formation comprises brick-red sandstones with large-scale, dune cross-bedding and is characterized by the presence of wind-rounded grains.

Lavas and interbedded sedimentary rocks are exposed in the river bed and on the south bank upstream (east) of the new road bridge. The dip here is about 10° to the west. Lavas on the north bank, beneath the new bridge, are difficult to access. The best section of the upper part of the volcanic formation is seen in the cliff below the old road, downstream (west) from NS 512 254 (Figure 4.12). Here tuffs, some containing wind-rounded sand grains, are interleaved with and overlain by the Mauchline Sandstone Formation. The latter is very well exposed in old quarries and cliffs around NS 511 254, where the large-scale dune bedding can be seen.

Most flows appear to be altered to a greater or lesser degree, and colour varies between grey and a purplish-red, although some very fresh material is preserved. Pseudomorphed olivines are a common feature on weathered surfaces, giving the rocks a characteristic speckled appearance. The lavas are fine grained, usually highly scoriaceous and amygdaloidal with mainly calcite and zeolite infills. Some flows contain larger cavities and preserve fossilized surface cracks infilled with reddish-brown sandstone. The fragmental volcanic rocks are predominantly lithic tuffs and volcaniclastic breccias. They usually comprise sub-angular to angular lapilli and blocks of olivine basalt, which are commonly amygdaloidal, in a matrix of finer material derived from weathered ash and lava. Some crystal-lithic tuffs may be present. Sedimentary rocks interbedded with the lavas are orange-red or brick-red, generally fine- to medium-grained, commonly pebbly, sandstones and less commonly siltstones and mudstones. Clasts in the sandstones are mostly basalt, reflecting weathering of contemporaneous lavas, tuffs and vent agglomerates. Some, but not all, sandstones also contain wind-rounded quartz grains.

The geochemical studies by Macdonald *et al.* (1977) and Wallis (1989) have provided many whole-rock analyses of the Mauchline lavas, 28 of which are from the Howford Bridge area. All of the latter are basalts or basanites. In contrast to the majority of lavas from earlier Carboniferous volcanism in the Midland Valley, these lavas have strongly alkaline characteristics and are mainly strongly silica-undersaturated (nepheline-normative), although Macdonald *et al.* (1977) and Wallis (1989) also identified some mildly alkaline, transitional (hypersthene-normative) types. They have distinctive isotopic and trace-element signatures (see 'Introduction' to this chapter).

Also notable at this site is an irregular sill of analcime-bearing olivine-dolerite that cuts the lavas (Geikie, 1897; Tyrrell, 1912, 1928b). It forms a cliff on the north bank of the river, between the old and new bridges, and is probably between 25 m and 30 m thick. It appears to have been intruded partly along the plane of relative weakness afforded by an intercalation of fissile sandstone and has chilled upper and lower margins. Xenolithic bodies of sandstone and basalt lava occur close to the sill's margins and pale-coloured segregation veins of analcime-syenite are well seen. Although this sill was formerly assumed to be contemporaneous with the Lugar Sill and hence only slightly younger than the lavas, it is now considered to be part of the Prestwick–Mauchline Sill-complex, of Palaeogene age (Mykura, 1967). A K-Ar mineral date of 58.4 ± 1.4 Ma from Howford Bridge (De Souza, 1979, recalculated by Wallis, 1989) is the main evidence for the age of this complex, although earlier studies of palaeomagnetism from several localities had reached the same conclusion (Armstrong, 1957).

Figure 4.12 Cliffs of the River Ayr near Howford Bridge, showing aeolian sandstones of the Mauchline Sandstone Formation, overlying poorly bedded tuffs of the Mauchline Volcanic Formation. (Photo: British Geological Survey, No. C2917, reproduced with the permission of the Director, British Geological Survey, © NERC.)

Interpretation

The Early Permian volcanic activity appears to have been a mixture of effusive and explosive events, interrupted by periods of relative quiescence during which sediments were deposited. Various features of the lavas, for example the scoriaceous surfaces and the presence of surface fissures infiltrated by sandstone, suggest that they were emplaced subaerially and no pillow lavas or hyaloclastites have been reported.

Lateral variations in thickness, lithology and facies are a feature of the Mauchline Volcanic Formation. This strongly suggests that lavas were probably erupted as localized events from a number of separate centres. Some 60 or so volcanic necks, many with intrusions of highly silica-undersaturated rock-types, including olivine analcimite and monchiquite, occur within a radius of 30 km and these may well have been the sources of both the lavas and the pyroclastic rocks. Many basic alkaline sills and dykes in the western Midland Valley are also thought to be contemporaneous with this volcanism (e.g. see **Lugar** GCR site report).

The composition, irregular lithofacies alternation, and sedimentary structures of the sedimentary rocks point to a mixture of aeolian and subaqueous deposition. Hence the overall palaeoenvironment appears to have been one of a spasmodically active volcanic field combined with increasingly arid, desert conditions, punctuated by seasonal periods of rainfall giving rise to sheet-floods and local lakes. Topography is thought to have been subdued with the lavas erupted on to a floodplain.

The strongly silica-undersaturated nature of these lavas was one line of evidence that led MacGregor (1948) to propose that volcanism in the Scottish sector of the Carboniferous–Permian Igneous Province of northern Britain became increasingly silica-understaurated with time. This was refined by Macdonald *et al.* (1977), who identified two magmatic or thermal cycles, each beginning with the production of hypersthene-normative magmas which then gave way to increasingly nepheline-normative types. The Mauchline lavas are part of the second of these cycles, but more recent work has suggested that this model is over-simplified (see Chapter 1).

Analyses of these lavas have contributed greatly to the overall model for the generation and evolution of Silesian and Early Permian magmas proposed by Wallis (1989) and summarized in Chapter 1. More specifically, they exhibit reduced levels of the most incompatible trace elements, because the lithospheric mantle, the usual source of such elements in the Midland Valley igneous rocks, had already been depleted by partial melting in late Namurian times which had resulted in the Troon Volcanic Member. However, Sr and Nd isotope ratios do still indicate some lithospheric interaction, in marked contrast to late Stephanian–Early Permian igneous rocks in areas such as Fife and East Lothian, which had been affected by partial melting responsible for the Stephanian tholeiitic intrusions (see Chapter 6).

A north-west–south-east to WNW–ESE structural control for both volcanism and sedimentation in the Permian basins of south-west Scotland was inferred by MacGregor (1948) and Mykura (1967) respectively and this has generally been interpreted as being a reflection of north-west–south-east and north–south rifting (McLean, 1978). More recent interpretations have related the basin development to the presence and re-activation of Caledonian structures in the underlying basement rocks (Anderson *et al.*, 1995; Coward, 1990, 1993, 1995). Coward's (1993) model of the tectonic evolution of the Midland Valley envisaged sinistral strike-slip movement on the Highland Boundary and Southern Upland faults continuing throughout the Carboniferous Period but being replaced by dextral strike-slip movement during end-Carboniferous and Early Permian times. The Mauchline Basin is situated between the ENE- to NE-trending Inchgotrick Fault in the north and the NE-trending Kerse Loch Fault to the south, and Rippon *et al.* (1996), whilst generally supporting Coward's model, suggested that these faults may have acted as extensional structures controlling basin formation and volcanism. However, they pointed out that, as dykes with petrological affinities to the Mauchline lavas and also the Late Carboniferous tholeiitic dykes have east–west trends, the extension may have been north–south.

Conclusions

The volcanic rocks that crop out at the Howford Bridge GCR site are representative of the Mauchline Volcanic Formation, the extrusive product of one of the youngest magmatic events in the Carboniferous–Permian Igneous Province of northern Britain. Many volcanic necks, plugs and sills in and around the Mauchline Basin are related to these rocks and they may have formed part of a larger volcanic field that included the comparable sequences of the Thornhill and Sanquhar basins to the south-east.

Old quarries that expose wind-deposited, dune-bedded, red sandstones of the overlying Mauchline Sandstone Formation are an added attraction at this site. The intimate association of these continental red beds with the volcanic rocks was a factor that first led geologists to suggest a Permian age for the volcanism, and plant remains have subsequently been found elsewhere in the Mauchline Basin that confirm an Early Permian age. Since both lithological and palaeontological evidence suggests that the volcanic rocks were erupted close to the Carboniferous–Permian boundary, they have international importance as a source of material for radiometric dating, and recently obtained dates have contributed to the currently accepted boundary age of 290 million years.

The lavas and tuffs at this site are mainly basaltic and some are very deficient in silica (basanites). They are some of the most silica-undersaturated and alkaline in the whole igneous province and hence are of considerable interest. They play an important role in developing a consistent model for the magmatic origin and development of the province, which in turn is of great relevance to the broader aspects of magmatism and basin development in Britain and north-west Europe during Late Palaeozoic times. An alkali dolerite sill in the eastern part of the site is of much younger, Palaeogene age and is related to similar sills on the Isle of Arran.

CARRON WATER, DUMFRIES AND GALLOWAY (NS 885 017–NS 887 024)

I.T. Williamson

Introduction

The gorge of the Carron Water, 4 km NNE of Carronbridge, Nithsdale and 0.5 km downstream from Jenny Hair's Bridge, is the type section for the Early Permian Carron Basalt Formation (Figure 4.13). The site is continuous with the Hapland Burn GCR site that represents the associated fluvial and aeolian sedimentary rocks (see Benton *et al.*, 2002).

The Carron Basalt Formation, defined by Brookfield (1978) from this type section, comprises basaltic lavas and some interbedded sedimentary units. It is restricted to the Thornhill Basin, a small N–S-elongated fault-bound outlier of Carboniferous and Permian rocks within the Southern Uplands, and to very small outliers in the adjoining Sanquhar Basin. Originally these lavas may have formed part of a more extensive volcanic field that included the volcanic rocks in the Mauchline Basin (see **Howford Bridge** GCR site report).

These volcanic rocks were identified by Geikie (1866, 1897) and were first described in some detail in the Geological Survey memoir for the Sanquhar and Thornhill coalfields (Simpson and Richey, 1936). A general description of the Thornhill Basin appears in the memoir for the adjacent Sheet 9 (McMillan, 2002) and aspects of the Permian sedimentology and stratigraphy were discussed by Brookfield (1978, 1980) and McMillan and Brand (1995). The basalts have been included in geochemical studies of Silesian and Permian igneous rocks of southern Scotland by Macdonald *et al.* (1977) and Wallis (1989) and have also been investigated as a potential source of gold that occurs as trace amounts in the associated red beds (Leake *et al.*, 1997). Brief descriptions of the GCR site and nearby localities have been included in field excursion guides (Brookfield, 1981; McMillan in Stone, 1996).

Description

The Carron Basalt Formation is exposed only intermittently within the northern and western parts of the Thornhill Basin. The sequence of lavas with associated thin breccias and sand-

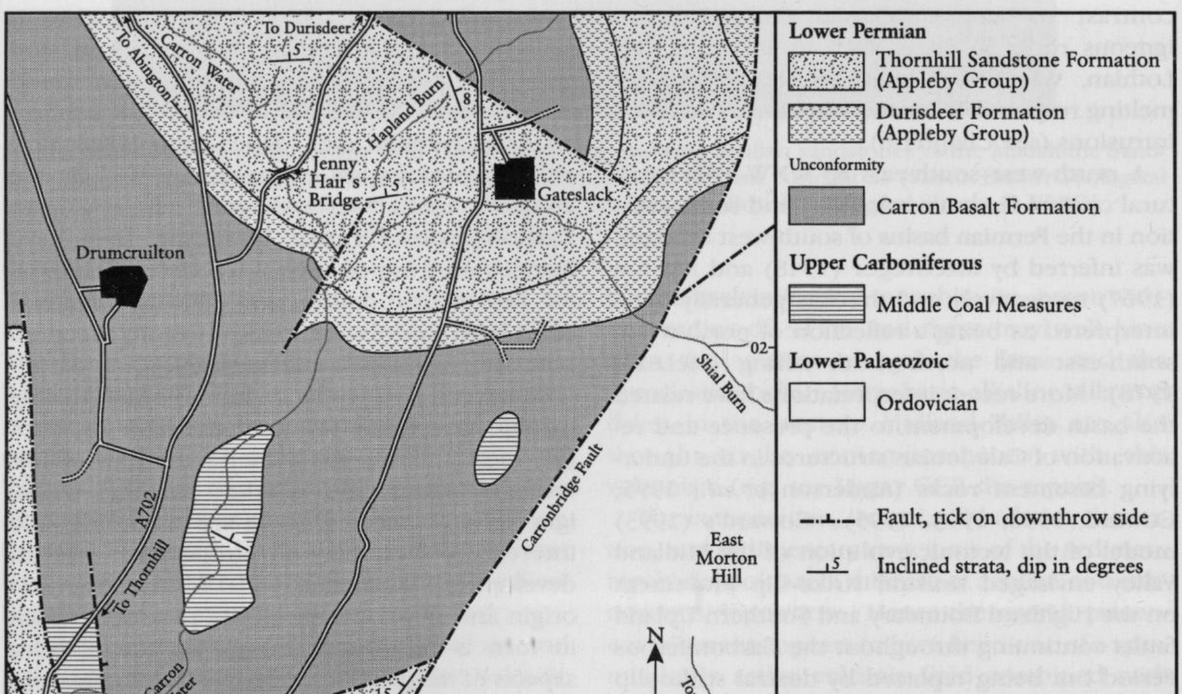

Figure 4.13 Map of the area around the Carron Water GCR site. Based on British Geological Survey 1:10 000 Sheet NS 80 SE (2000).

stones is no more than 50 m thick at maximum, though thicknesses of 20 m are most usually quoted (e.g. McMillan, 2002). It unconformably overlies mainly reddened Middle Coal Measures strata, though in the south-east it rests upon Lower Palaeozoic rocks. It is succeeded by the Durisdeer Formation and the Thornhill Sandstone Formation of the Lower Permian Appleby Group.

The Carron Water GCR site is the type locality for the Carron Basalt Formation, where 20 m or so of lavas and sedimentary rocks dip gently to the north. The type succession of the formation (after Simpson and Richey, 1936) is shown below.

Top
Sandstone, brick-red with occasional 'blocks' of basalt
Sandstone, brick-red, cross-bedded, aeolian
Breccia, basaltic
Non-exposed gap
Olivine basalt, amygdaloidal; 2 flows, each with fissured upper surfaces
Sandstone, red, fine grained
Olivine basalt, amygdaloidal
Sandstone, very fine-grained, with basaltic pebbles in upper part
Non-exposed gap
Carboniferous sedimentary rock
Bottom

Locally, the base of the volcanic formation is a breccia with small angular clasts of greywacke and basalt in a sandy matrix. The presence of basaltic clasts indicates that lavas were already present and were being eroded elsewhere in the basin. Some basalts incorporate wind-blown sand in their matrix (Brookfield, 1980). The lavas, for the most part, comprise deeply and extensively weathered olivine basalts, 1–3 m thick (Figure 4.14). Olivine microphenocrysts and other ferromagnesian phases are easily seen on weathered surfaces as they are pseudomorphed by amorphous mixtures of 'serpentine', haematite, chlorite and clay minerals, giving a red speckled appearance to the rock. All three flows are amygdaloidal to a greater or lesser degree, but locally they have a slightly more massive facies overlain by a thicker amygdaloidal zone. This upper part is often reddened and fissured. Where the flows are overlain by contemporaneous sedimentary rocks, these fissures have been partially infilled, and neptunian dykes of sandstone are quite common. The top of the formation is a basalt breccia, irregularly overlying fissured, amygdaloidal basalt. However, the contact between basalt and breccia cannot be seen.

The top of the Carron Basalt Formation interdigitates with the base of the Durisdeer Formation. The latter comprises a variable unit, some 70 m thick in the Hapland Burn, of arenaceous sedimentary rocks dominated by polymict conglomerates, pebbly sandstones, cross-bedded sandstones and tabular sandy breccias (Brookfield, 1978). Clasts in the conglomerates and breccias are dominated by locally derived basalt, up to boulder size, but also include local Carboniferous and Lower Palaeozoic sedimentary rocks. These coarse-grained fluvial lithologies interdigitate with and pass upwards into aeolian dune-bedded sandstones that typify the overlying Thornhill Sandstone Formation.

There are few analyses of lavas from the Thornhill Basin (Macdonald *et al.*, 1977; Wallis, 1989). Although the latest Carboniferous and Early Permian igneous rocks of south-west Scotland are dominantly alkaline and silica-undersaturated, the lavas of the Thornhill Basin, like those of the Mauchline Basin, show a range of compositions from hypersthene-normative (transitional) basalts to nepheline-normative alkali basalts and basanites.

Interpretation

Because of its association with red fluvial and aeolian strata, the Carron Basalt Formation has long been considered to be Permian in age (Geikie, 1866, 1897; Simpson and Richey, 1936). Plant remains in beds intercalated with similar flows in the Mauchline Basin have been assigned to the earliest Permian (Wagner, 1983), and by inference the Carron Basalt Formation is probably also of earliest Permian age. Being so close to the Carboniferous–Permian boundary, the basalts therefore have potential international significance as a source of material for radiometric dating, although finding fresh material could be difficult.

The palaeoenvironment of the Thornhill Basin during the volcanic period is best assessed by considering both the lavas and the facies of the associated sedimentary rocks. The volcanism appears to have been short-lived and intermittent. Locally, flows show reddened upper surfaces suggesting atmospheric weathering, and the incorporation of unconsolidated sand into the matrix of some flows and the sandstone dykes in fissures also point to surface exposure. The lavas were emplaced subaerially; there is no evidence by way of pillow structures or

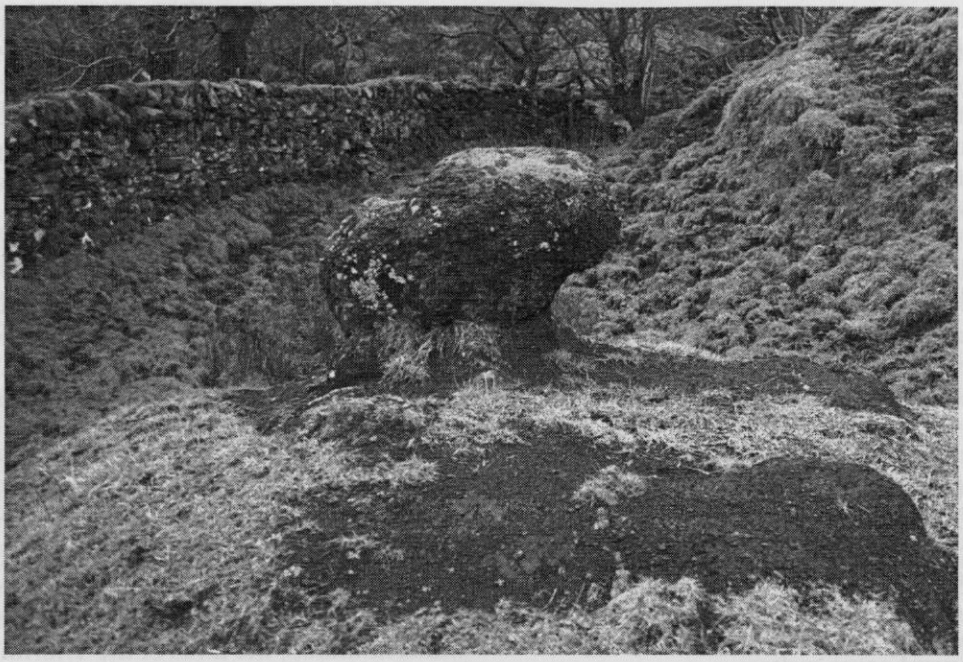

Figure 4.14 Residual 'core' within heavily-weathered basalt lava of the Carron Basalt Formation on the west bank of the Carron Water GCR site. (Photo: K.M. Goodenough.)

hyaloclastites for the existence of bodies of standing water, despite the presence of interbedded, waterlain sedimentary rocks.

The lower sandstones and those infilling fissures on the flow surfaces contain mainly subangular grains, typical of immature fluvial facies. Brookfield (1978, 1980) and McMillan and Brand (1995) have interpreted the basal breccias and conglomerates of the Durisdeer Formation as piedmont and minor stream-flood deposits with some alluvial fan sheet-flood sands and breccias and marginal fluvial facies. There are some interbedded aeolian sandstones and climatic conditions became progressively more arid, but true desert conditions may not have been fully established until well after the volcanic period. The succeeding beds of the Thornhill Sandstone Formation contain mainly well-rounded grains and polished and faceted pebbles. They are dominated by desert dune sands and a few interdune sheet deposits.

The Thornhill Basin is one of a number of now isolated Permian sedimentary basins in the Southern Uplands that are orientated perpendicular to the north-east–south-west Caledonian fabric of the underlying rocks. They developed under extensional regimes, with their shape and orientation controlled by the re-activation of deep-seated structures in the basement (Anderson *et al.*, 1995). Limited transitional to alkaline volcanism was associated with the early phases in the rift-history of the basin and may have been contiguous with other Permian volcanic sequences in southern Scotland, for example the Mauchline Volcanic Formation (see **Howford Bridge** GCR site report).

Conclusions

The Carron Water GCR site contains the type section for the Carron Basalt Formation, a series of subaerial, olivine basalts within the Early Permian 'red bed' sequence of the Thornhill Basin. The interaction between volcanism and contemporaneous sedimentation is a feature of the site that enables reconstructions of both palaeoenvironment and palaeogeography.

The basalts are among the youngest products of the Carboniferous–Permian Igneous Province of northern Britain and hence are important in any consideration of the overall magmatic evolution. Together with interbedded fluvial and aeolian sedimentary rocks, they are also critical to a full understanding of the complex interplay between magmatic events, sedimentation and basin tectonics in northern Britain and throughout north-west Europe during Early Permian times.