Carboniferous and Permian magmatism in Scotland

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Abstract: Extensional tectonics to the north of the Variscan Front during the Early Carboniferous generated fault-controlled basins across the British Isles, with accompanying basaltic magmatism. In Scotland Dinantian magmatism was dominantly mildly alkaline–transitional in composition. Tournaisian activity was followed by widespread Visean eruptions largely concentrated within the Scottish Midland Valley where the lava successions, dominantly of basaltic–hawaiitic composition, attained thicknesses of up to 1000 m. Changing stress fields in the late Visean coincided with a change in the nature of the igneous activity; subsequently, wholly basic magmatism persisted into the Silesian. As sedimentary basin fills increased, sill intrusion tended to dominate over lava extrusion. In the Late Carboniferous (Stephanian) a major melting episode, producing large volumes of tholeiitic magma, gave rise to a major dyke swarm and sills across northern England and Scotland. Alkali basaltic magmatism persisted into the Permian, possibly until as late as 250 Ma in Orkney. Geochemical data suggest that the Carboniferous–Permian magmas were dominantly of asthenospheric origin, derived from variable degrees of partial melting of a heterogeneous mantle source; varying degrees of interaction with the lithosphere are indicated. Peridotite, pyroxenite and granulite-facies basic meta-igneous rocks entrained as xenoliths within the most primitive magmas provide evidence for metasomatism of the lithospheric mantle and high-pressure crystal fractionation.

The Variscan Orogeny, which came about through collision of the African portion of Gondwana and Laurussia during the Carboniferous, resulted in the welding of the two into the supercontinent of Pangaea (Scotese 1984). North of the Variscan Front, which traverses the southern parts of Ireland, Wales and England, Great Britain and Ireland were composed of continental crust that had remained essentially undeformed since the preceding Caledonian Orogeny. This continental terrane was affected, throughout the Carboniferous and much of the Permian, by changing stress fields (principally extensional) that resulted in strike-slip faulting and monoclinal flexuring with attendant basaltic magmatism.

Although the Carboniferous basaltic magmas generated in response to these tectonic adjustments ranged from tholeiitic through transitional types to strongly alkaline, the bulk of the lavas and their associated shallow intrusions are transitional–mildly alkaline. However, at a critical stage in the Late Carboniferous (Stephanian) a remarkable tholeiitic event produced a major regional dyke swarm, with associated sills, across northern England, much of Scotland and the North Sea. Magmatism, which continued in Scotland into the Permian on a subdued scale, principally involved alkaline magmas. The distribution of the lava outcrops and associated vents, necks and plugs in Scotland is shown in Figure 1.

The Carboniferous magmatic activity is of interest as it represents an early example of the type of continental intra-plate, extension-related basalt magmatism that was to become globally widespread in Mesozoic and Cenozoic times. The Stephanian tholeiitic event has affinity to continental flood basalt magmatism despite its intrusive, rather than extrusive, nature in Britain. The eruption of primitive, commonly mantle-xenolith-bearing, basanitic–melanephelinitic magmas also marks an unusually early example of the genre, older mantle-xenolith-bearing magmas generally being kimberlitic or lamprophyric rather than basaltic.

Sedimentary basins within the Scottish Midland Valley (SMV) accumulated up to 5 km of sedimentary and volcanic rocks during the Carboniferous (Guion *et al.* 2000). Because of the relatively low density of these supercrustal strata there was a tendency for progressively younger magma batches to generate extensive sills as the basin fills thickened; consequently,

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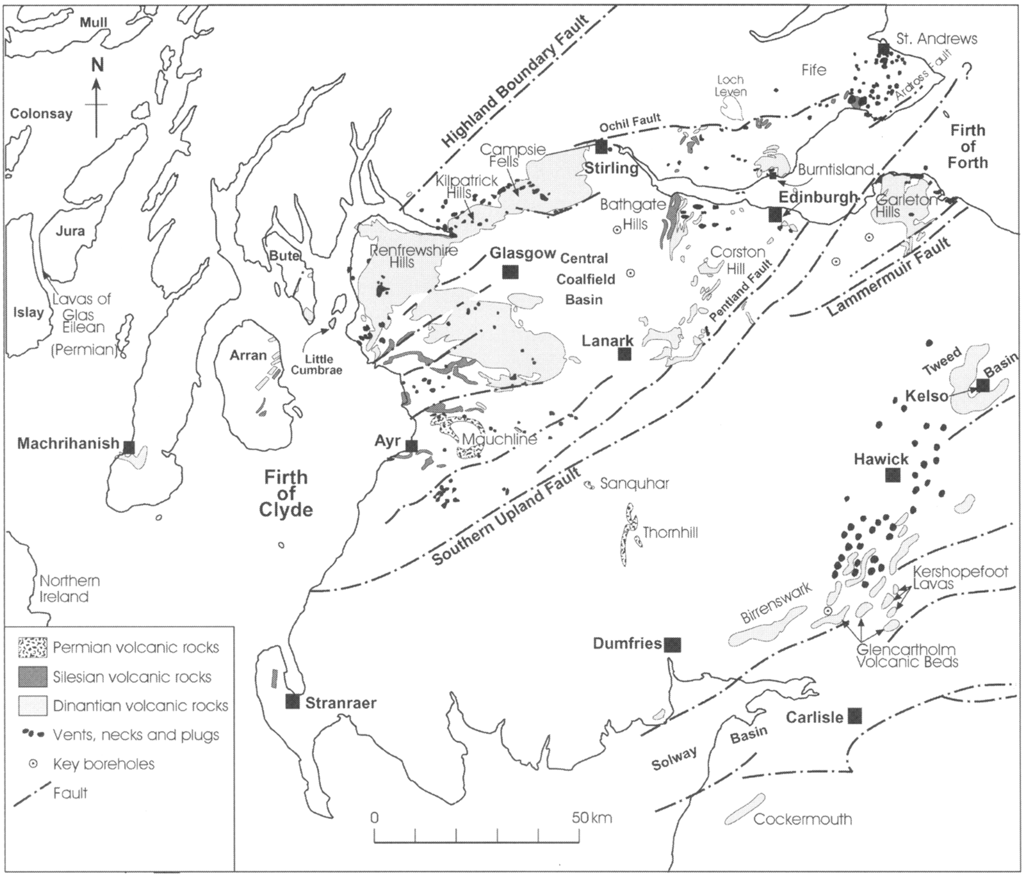

Fig. 1. Map of the Midland Valley and southern Scotland showing the outcrops of Dinantian, Silesian and Early Permian volcanic rocks, and the major structural components. After Leeder (1974), Cameron & Stephenson (1985) and the British Geological Survey (*Tectonic Map of Britain, Ireland and Adjacent Areas*, 1996).

the ratio of intrusive to extrusive products generally appears to have risen as the basins filled.

After the end of Caledonian supra-subduction zone magmatism in the late Silurian–early Devonian there was a notable absence of igneous activity over most of northern Britain and Ireland, although pre-Carboniferous magmatism persisted in Shetland through to the Late Devonian. The renaissance of magmatism early in the Tournaisian in southern Scotland marked a significant compositional change from the preceding calc-alkaline supra-subduction zone activity (Smedley 1986*a*). Modest volumes of Tournaisian lavas heralded much more vigorous Visean magmatism. Visean volcanoes erupted over a wide region from the Scottish Borders to the southern Highlands (Kintyre) and were particularly concentrated in the SMV. As volcanism continued intermittently from *c.* 350 Ma in the Tournaisian into the mid-Permian, possibly terminating as late as 250 Ma in Orkney, the Carboniferous–Permian intraplate activity extended over a remarkable time-span of up to 100 Ma.

Generation of intermediate and silicic magmas, inferred to be fractional crystallization residues from parental basalt magmas, was mainly confined to the Dinantian. This restriction is attributed to the larger volumes of parental magmas and their relatively low overall ascent rates, with generation of crustal (Moho) underplated and shallower-crustal magma chambers in which varying degrees of differentiation were attained. In contrast, alkali basalt magmas produced in the late Visean, Silesian and Permian rarely evolved beyond the hawaiitic stage. A revision of the time v. space diagram for the Scottish Carboniferous–Permian activity (from Stephenson *et al.* 2003), first presented

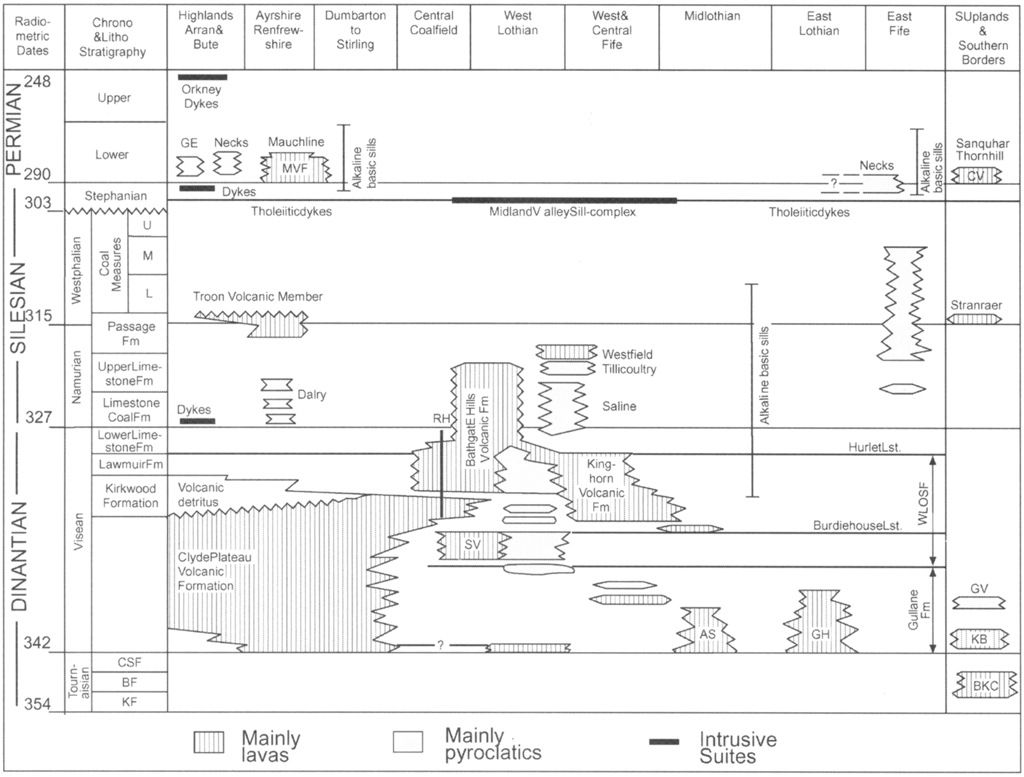

Fig. 2. Lithostratigraphical and geographical distribution of Carboniferous and Early Permian volcanic rocks in Scotland plus approximate age ranges of major intrusive suites. The vertical scale shows stratigraphical range and not thickness of volcanic successions. Radiometric dates from Gradstein & Ogg (1996), after Read *et al.* (2002). AS, Arthur's Seat Volcanic Formation; BF, Ballagan Formation; BKC, Birrenswark Volcanic Formation, Kelso Volcanic Formation and Cockermouth lavas; CSF, Clyde Sandstone Formation; CV, Carron Volcanic Formation; GE, Glas Eilean Lavas; GH, Garleton Hills Volcanic Formation; GV, Glencartholm Volcanic Beds; KB, Kersehopefoot Basalts; KF, Kinnesswood Formation; MVF, Mauchline Volcanic Formation; RH, Rashiehill Borehole; SV, Salsburgh Volcanic Formation; WLOSF, West Lothian Oil-shale Formation. (Fife and SE Scotland formation names omitted.)

by Francis (1965), is given as Figure 2 (after Read *et al.* 2002; see also Monaghan & Pringle 2004).

Tournaisian volcanism

The earliest Carboniferous activity in Scotland occurred along the fault-controlled northern boundaries of the developing Solway and Northumberland basins, as well as in the separate Tweed Basin (Fig. 1) (Leeder 1974; Leeder *et al.* 1989; Chadwick *et al.* 1995). The main trough incorporating these basins is a complex ENE-trending half-graben (Read *et al.* 2002). Subaerial eruptions gave rise to a discontinuous crop of lavas, traceable for *c.* 96 km ENE across southern Scotland from the northern coast of the Solway Firth (Fig. 1). These lavas compose the Birrenswark Volcanic Formation; a sequence of transitional basalts and hawaiites, with sedimentary intercalations up to 90 m thick (Pallister 1952; Elliott 1960). The formation is overlain conformably by a thick succession of Tournaisian sedimentary strata (Lumsden *et al.* 1967). The Cockermouth Lavas, on the southern margin of the Solway Basin in northern England, are believed to be of similar age.

Some 50 km to the NE, in the Tweed Basin, a 120 m-thick sequence of basaltic–trachyandesitic lavas constitutes the Kelso Volcanic Formation (Eckford & Ritchie, 1939; Tomkeieff 1953). These are believed to have erupted in response to the same tensional episode as the Birrenswark lavas. Many of the abundant diatremes and intrusive basaltic–trachyandesitic plugs, scattered to the SW of the Tweed Basin, are inferred to mark the conduits through which the Birrenswark and Kelso lavas erupted (Fig. 1).

Alkaline and peralkaline felsic intrusions in southern Scotland (e.g. the trachyte and riebeckite rhyolite of the Eildon Hills: McRobert 1914) and the quartz-trachyte and phonolitic trachyte of Skelfhill Pen (McRobert 1920), formerly thought to be related to the later (Visean) Glencartholm volcanism, could be Tournaisian, at least in part, on the basis of one new Ar–Ar date (Monaghan & Pringle 2004).

Early–mid-Visean volcanism

During the latest Tournaisian or earliest Visean, after some 10 Ma of quiescence, volcanism resumed in south and central Scotland at 342–335 Ma (Monaghan & Pringle 2004), across a zone *c.* 200 km wide, from Kintyre in the west to the Garleton Hills in the east. This episode saw the production of over 90% by volume of all the Scottish lavas produced in the Carboniferous and Permian, the original volume of which might have approached 6000 km^3 (Tomkeieff 1937). These successions are dominated by transitional–mildly alkaline basalts, hawaiites and mugearites, but include trachytes and, more rarely, rhyolites.

In the far south of Scotland, eruptions of basalt and hawaiite lavas occurred along much the same zone as that affected by the preceding Birrenswark volcanism (Lumsden *et al.* 1967; Day 1970), forming the Kersehopefoot succession (60 m maximum) and, subsequently, the basaltic and trachytic pyroclastic rocks and lavas of the Glencartholm Volcanic Beds (180 m maximum).

The Garleton Hills Volcanic Formation crops out to the east of the province between the subsurface extension of the Southern Upland Fault (Max 1976; Floyd 1994) and the Lammermuir Fault, and thus lies outside the SMV itself (Fig. 1). This formation is up to 520 m thick. Basaltic pyroclastic rocks at the base are overlain by basaltic, trachybasaltic and trachyandesitic lavas (not necessarily in that sequence), culminating in thick (20 m or more) quartz-trachyte lavas (McAdam & Tulloch 1985; Davies *et al.* 1986). Some of the trachybasaltic ('kulaite') lavas may have been leucite-bearing (Bennett 1945). Notable phonolitic trachyte intrusions occur within this lava field. Although these have not been dated, they are generally assumed to be a little younger than the lava series.

In Edinburgh, a 400–500 m-thick lava and pyroclastic succession, together with associated intrusions, dominates the city landscape in and around Holyrood Park (Clark 1956; Black 1966) whilst a more restricted, 90 m-thick succession forms Craiglockhart Hill, 6 km to the SW (Fig. 1).

In the west of the SMV, lavas that crop out in the upland regions north, west and south of Glasgow constitute the Clyde Plateau Volcanic Formation (Figs 1 and 2). This formation, involving the most extensive and voluminous of all the Visean lava successions, rests unconformably on Upper Devonian–Lower Carboniferous (Tournaisian) strata, but is locally conformable with the highest known Tournaisian strata (Paterson & Hall 1986). The close association between the maximum pre-eruptive erosion of strata and the thickest developments of volcanic rocks suggests that, locally, the unconformity may have been due to magmatic updoming prior to the onset of the Visean eruptions (Monro 1982; Forsyth *et al.* 1996). The Clyde Plateau Volcanic Formation accumulated to form a significant topographical feature that was subsequently denuded and gradually overlapped by younger Visean sedimentary strata. Major faults subdivide the Clyde Plateau Volcanic Formation into several discrete blocks (Fig. 1), correlation between which presents difficulties. The faulting involved sinistral strike-slip displacements, with volcanism occurring in localized zones of transtension (Read *et al.* 2002). The Clyde Plateau lavas are mainly alkali basalts, hawaiites and mugearites (trachybasalts and trachyandesites), although trachytic and rhyolitic flows are also present locally. Phonolitic trachyte and rhyolitic intrusions also occur.

Notable contributions to elucidating the structure and evolution of the Clyde Plateau volcanic rocks include those in Geological Survey Memoirs (e.g. Francis *et al.* 1970; Paterson *et al.* 1990; Hall *et al.* 1998; Forsyth *et al.* 1996; Monro 1999). Although the widespread volcanic outcrops terminate abruptly to the SE at the Inchgotrick Fault, the Heads of Ayr Neck on the coast a few kilometres SW of Ayr (Whyte 1963) may represent a small isolated volcano of similar age (Fig. 1).

The Clyde Plateau Volcanic Formation attains its maximum thickness, approximately 1000 m, in the Renfrewshire Hills (Fig. 1), from where it thins markedly southwards (Paterson *et al.* 1990; Monro 1999). The lavas probably never extended significantly farther to the NW than their present outcrop (George 1960; Whyte & MacDonald 1974). To the west, outlying volcanic successions on the islands of Little Cumbrae, Bute and Arran (Fig. 1) are thin, suggesting that the succession attenuated dramatically westwards from the main outcrops. Although the Clyde Plateau lavas may continue for some distance to the east beneath the Central Coalfield Basin of the Midland Valley, seismic evidence suggests that they also thin abruptly in this direction and are replaced by a thick sedimentary succession (Hall 1971).

Whilst the surface eruptions are inferred to have been supplied through dykes in the crystalline basement, erosion levels are generally too shallow to reveal these feeder systems. However, large ENE- to NE-trending basic dykes (up to 12 m wide) on Great Cumbrae Island, west of the Clyde Plateau, and smaller but similar dykes on Bute and in the Renfrewshire Hills may be representative of a feeder swarm (Paterson *et al.* 1990; Monro 1999).

Around Machrihanish in south Kintyre (Fig. 1), a volcanic succession up to 400 m thick, lies north and west of the Highland Boundary Fault, overstepping Lower Devonian strata onto the Neoproterozoic or Lower Palaeozoic metasedimentary rocks of the Dalradian Supergroup (McCallien 1927). Although the Machrihanish succession has been assigned to the Clyde Plateau Volcanic Formation, it is likely that it constituted an entirely separate lava field. The lava field may have had connections with basaltic lavas in the vicinity of Ballycastle, Northern Ireland, that were also erupted on the northern side of the Highland Boundary Fault.

Late Visean–Westphalian volcanism

From late Visean times and through the Namurian there were changes in the regional stress field. These were attended by new structural elements and, in the central and western SMV, the tectonic units were bounded by WSW–ENE faults. In the north and east of the SMV, a system of N–S and NNE–SSW asymmetric basins developed, reflecting the onset of E–W extension. Accompanying volcanism was largely confined to the structural highs and the hinges between basins and highs.

The late Visean lavas were entirely basaltic in contrast to the wide compositional variety within the earlier volcanic successions described above. They occur within and around the West Lothian Oil-shale Basin, midway between the Clyde Plateau and the Garleton Hills (Fig. 1). Initial activity was, however, probably contemporaneous with the later phases of the essentially subaerial Clyde Plateau Volcanic Formation. Thick and widespread pyroclastic rocks mark the base of the Bathgate Hills Volcanic Formation (Figs 1 and 2), which rests directly on the Clyde Plateau Volcanic Formation to the west. The initial subaerial lava pile was overlapped and volcanism continued within coastal plain, lagoonal or shallow-marine environments. These were a precursor to the Silesian volcanic settings as the lavas of the Bathgate Hills interdigitated with the sedimentary succession throughout the remainder of the Visean and well into the Namurian, giving a sequence some 600 m thick (Cadell 1925; Smith *et al.* 1994; Cameron *et al.* 1998). Subsidence kept pace with accumulation and there were periodic marine incursions. The presence of fossil soil horizons (boles) indicates subaerial weathering, and volcanoes are inferred to have built up as islands in the shallow seas, surrounded by fringing reefs (Jameson 1987).

Late Visean volcanic activity also occurred in the Burntisland area of Fife (Fig. 1), where up to 485 m of basaltic lavas with subordinate pyroclastic rocks and volcaniclastic sedimentary rocks constitute the Kinghorn Volcanic Formation. The succession was dominantly subaerial, but periodic submergences resulted in some pillow lavas and hyaloclastites.

In Fife (Fig. 1), bedded tuffs provide evidence for volcanic activity at numerous volcanic centres throughout the Silesian. Most of this activity was phreatomagmatic, driven by the interaction of magma with water in the sedimentary pile. Over 100 volcanic necks have been recorded in East Fife (Forsyth & Chisholm 1977), cutting strata ranging in age from late Visean to early Westphalian. Radiometric dating suggests a Namurian–Westphalian age for most of the necks (Forsyth & Rundle 1978; De Souza 1979; Macintyre *et al.* 1981), although some within the range 295–288 Ma (Wallis 1989) should be considered as early Permian. The relationship between the necks and the NE-trending, dextral strike-slip Ardross Fault (Fig. 1) provides a classic example of fault-controlled volcanism (Francis & Hopgood 1970).

In the west of the Midland Valley, phreatomagmatic activity from numerous short-lived local volcanic centres occurred in the early Namurian in north Ayrshire. Tectonic instability in the late Namurian–early Westphalian was accompanied by extensive renewed volcanism in Ayrshire. At this stage (during Passage Formation time, Fig. 2) there were changes in the structural pattern, and movements on ENE- and NE-trending faults occurred during a dextral transpressive phase (Read *et al.* 2002). The Ayrshire lavas, almost exclusively of subaerial basalt, lie within the Passage Formation. They are assigned to the Troon Volcanic Member, which extends beneath the Coal Measures of most of the northern Ayrshire Basin, and attains a maximum thickness of *c.* 162 m (Monro 1999). Thinner representatives of these eruptions occur on the Isle of Arran, in Kintyre, near Stranraer and possibly in Northern Ireland (Richey *et al.* 1930). Their most notable feature is their relatively decomposed state as a result of deep tropical weathering, giving rise to the Ayrshire Bauxitic Clay, formerly of economic importance. By this time volcanism had ceased in the Bathgate area (Fig. 2) but persisted in Fife.

Alkaline basic sills and dykes

Although subordinate minor intrusions, such as plugs, dykes and sills, formed an integral part of the early–mid-Visean igneous activity, the more extensive basic sill complexes of the SMV and regional dyke swarms throughout Scotland are of late Visean age or younger (Figs 2 and 3). These represent voluminous injections of alkaline basic magma that must be considered together with their coeval, but locally less voluminous, extrusive counterparts.

Francis (1968) noted that late Visean and Silesian lavas tend to occur where the Carboniferous sediments were thin or undergoing uplift, and he proposed that the sediments in the adjacent, progressively deepening, basins were of insufficient density to support extended columns of magma. Being unable, on density grounds, to rise to the surface, the magmas spread laterally to form sills (Francis 1991). Field and borehole evidence indicates that many of the sills were injected into poorly lithified, water-saturated sediments and hence can be regarded as only slightly younger than their host rocks (Walker & Francis 1987). Some show close geographical and petrological association with volcanic necks that mark the sites of phreatomagmatic eruptions; Francis & Walker (1987) suggested that degassed magma in some of the volcanic pipes provided the feeders for the alkaline sills.

The sills (and scarce dykes) are mostly varieties of alkali dolerite or alkali gabbro. Strongly undersaturated, feldspar-poor or feldspar-free rocks tend to occur in thin sills and dykes: these were formerly classified as 'monchiquitic' but are better termed olivine analcimite and olivine nephelinite (melanephelinite). They grade, however, into analcime basanite, nepheline basanite and, rarely, leucite basanite.

In the eastern part of the SMV, alkali dolerite sills were repeatedly emplaced from the late

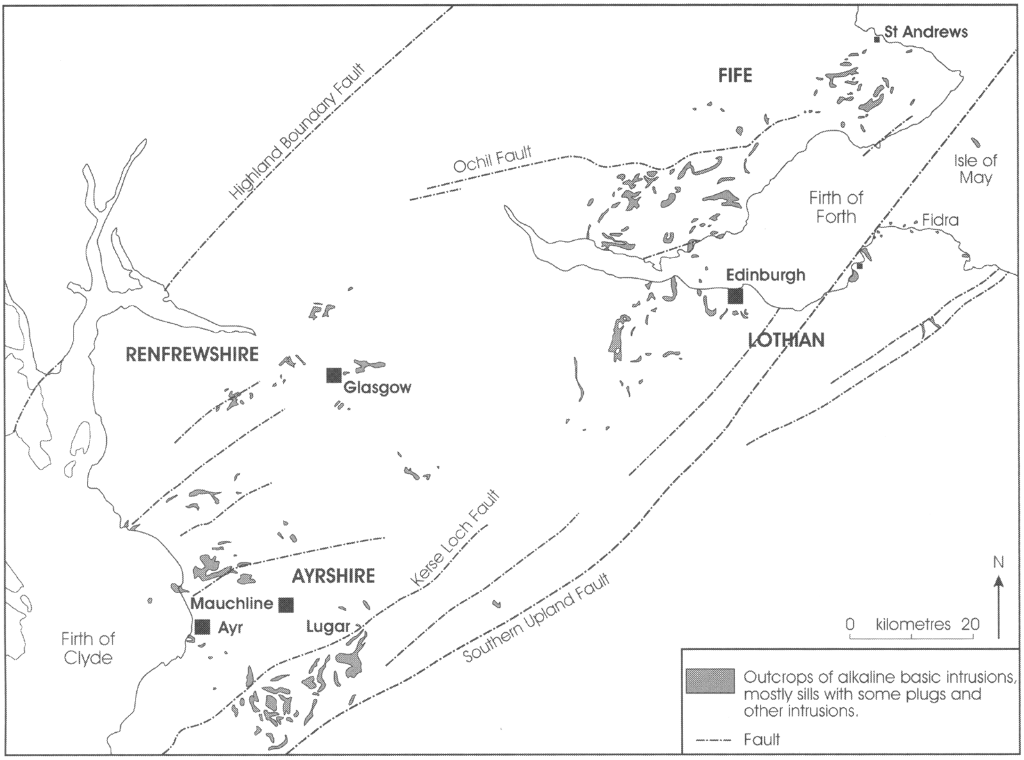

Fig. 3. Distribution of alkali dolerite sills in the Scottish Midland Valley. (After Cameron & Stephenson 1985.)

Visean to the early Westphalian. Typical examples to the NW of Edinburgh have been dated recently at 332–329 Ma (Monaghan & Pringle 2004), and hence were contemporaneous and probably comagmatic with the volcanism at Burntisland, the Bathgate Hills and western Fife. In west and central Fife, a major sill-complex extends over 750 km^2 and has a total volume of 7.25 km^3 (Francis & Walker 1987).

In the Glasgow–Paisley area and in the Ayrshire Basin in the SW of the SMV, most of the olivine dolerite sills are of late Stephanian–early Permian age, although others are probably counterparts of the Namurian Troon Volcanic Member. Some silica-undersaturated alkali dolerite sills cut the Westphalian Coal Measures Group but not the early Permian Mauchline Sandstone Formation and may, accordingly, be slightly older than, or broadly coeval with, the Early Permian volcanism. An $^{40}Ar/^{39}Ar$ age of 288 ± 6 Ma obtained from the Lugar Sill in Ayrshire (Henderson *et al.* 1987) is supported by the new data of Monaghan & Pringle (2004). However, the problem as to whether some of the intrusions dated in the range 298–292 Ma should be considered as latest Carboniferous or earliest Permian depends on the timescale used: the problem of the age of the Carboniferous–Permian boundary is addressed by Monaghan & Pringle (2004).

The Lugar Sill developed from several injections of progressively less evolved alkali basalt magma from a deeper fractionating magma chamber, followed by a pulse of olivine-rich magma that differentiated *in situ* (Henderson & Gibb 1987). This occurrence, together with other examples, suggests that compositionally stratified magma chambers developed beneath the Midland Valley.

South of the Southern Upland Fault, thin alkali dolerite sills and NW-trending dykes in the Sanquhar Basin cut the Coal Measures (Simpson & Richey 1936) and are presumed to be intrusive equivalents of the early Permian volcanic rocks preserved as small outliers in the basin. An alkali olivine-dolerite sill within the Coal Measures at Machrihanish in Kintyre is also probably of early Permian age.

Widespread dykes of camptonite and monchiquite in the Hebrides and western Highlands have long been assumed, on petrographic grounds, to be of Carboniferous–Permian age (e.g. Richey 1939). In a major review of the whole suite, Rock (1983) recognized over 3000 dykes. However, Morrison *et al.* (1987) claimed that a considerable proportion may be Caledonian in age; nevertheless, K–Ar studies confirmed a Late Carboniferous–Permian age for most of the dykes, and Baxter & Mitchell (1984) suggested that the three general trends recognized may represent separate tectono-magmatic events (Fig. 4).

- E–W-trending dykes, dated at *c.* 326 Ma, are dominant in the central part of the northern Highlands. This age according to the Gradstein & Ogg (1996) timescale is earliest Namurian. A comparable date for these swarms was suggested by palaeomagnetic measurements (Esang & Piper 1984).
- Late Stephanian–early Permian dykes, dated at *c.* 290 Ma, trend NW–SE in the western and SW Highlands and Islands. A NNW-trending dyke on Mull yielded an Ar–Ar age of 268 ± 2 Ma (Upton *et al.* 1998).
- A late Permian dyke event at *c.* 250 Ma, forming the WSW–ENE Orkney Swarm.

These late Carboniferous–Permian Highland dykes include the most primitive silica-undersaturated, alkaline basic igneous rocks known in Britain.

Stephanian tholeiitic intrusions

Stress patterns changed rapidly from the late Westphalian–early Permian and several phases of tectonism are recognizable (Read *et al.* 2002). The first, involving E–W compression, resulted in basin formation and dextral strike-slip motion on major Caledonide fracture systems in the SMV. A second phase involving N–S compression was followed by one of N–S tension, which activated numerous E–W faults and accompanied (or gave rise to) a very significant magmatic event at *c.* 300 Ma (Stephenson *et al.* 2003 and references therein). This short-lived Stephanian event produced dykes and sills over a wide region, although no extrusive products are known (Fig. 5). In contrast to the transitional–alkaline basaltic magmatism that characterized northern Britain throughout most of the Carboniferous, these Stephanian intrusions involved silica-oversaturated tholeiitic basalt magmas (Walker 1935; Dunham & Strasser-King 1982; Stephenson *et al.* 2003).

The dykes constitute a swarm, some 200 km wide, trending broadly WSW–ENE to E–W. Extending over 300 km from Barra (Outer Hebrides) and Kintyre in the west to the east coast of Scotland, it constitutes one of the major Phanerozoic dyke swarms of NW Europe. Offshore to the east, the swarm may continue at least as far as the Central Graben of the North Sea (Smythe 1994). Locally, some dykes are deflected to a NE trend along the Highland Boundary Fault. In the

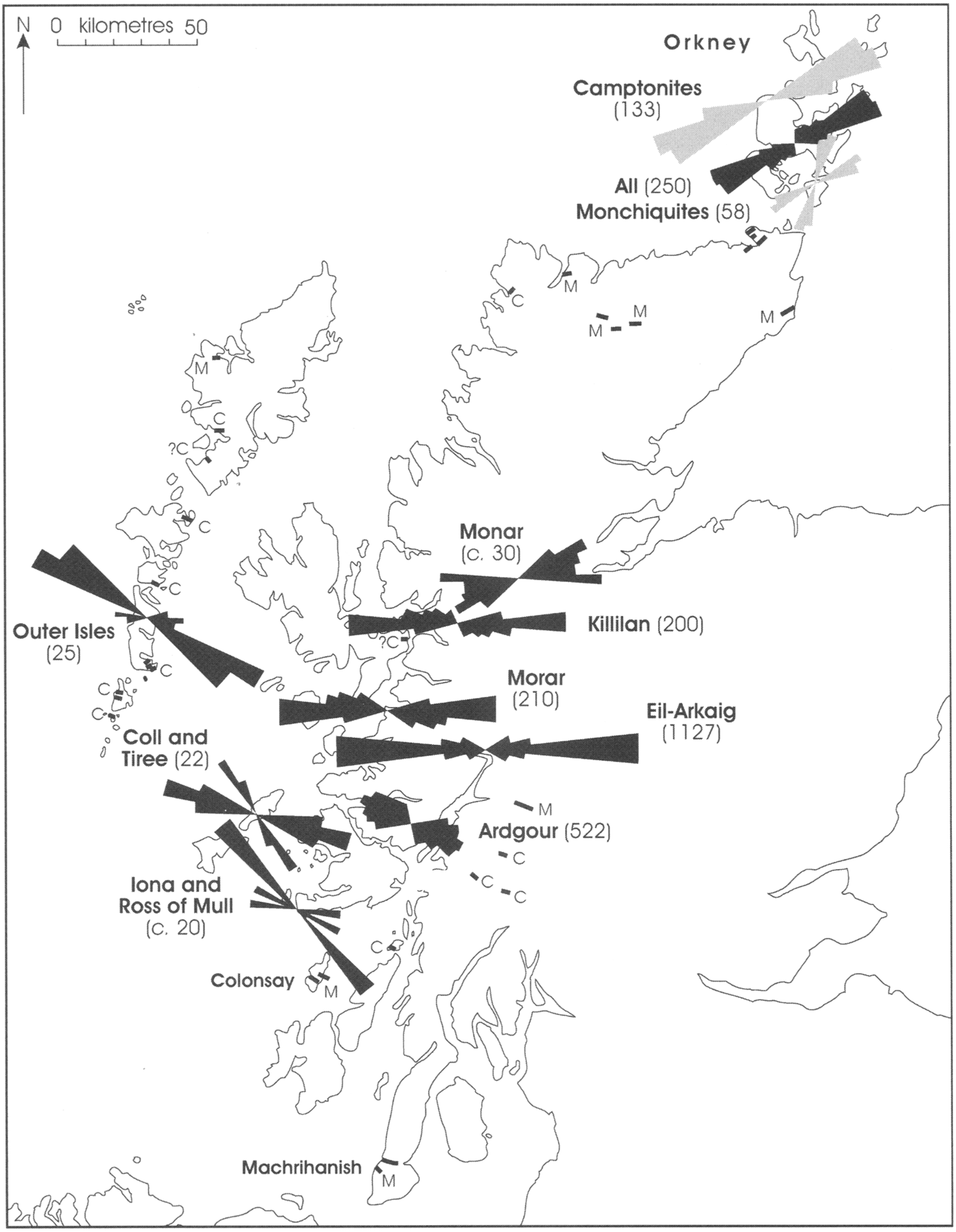

Fig. 4. Map showing the location and azimuth distribution of the main alkaline lamprophyre (camptonite and monchiquite) dyke swarms of the Northern Highlands. Azimuth distributions are presented as total percentage of dykes in each swarm with a particular orientation; thus, long arms indicate swarms trending more uniformly than short ones. The number of dykes recorded in each swarm is shown in brackets. Isolated occurrences of monchiquite and camptonite are shown by M and C, respectively. (After Rock 1983).

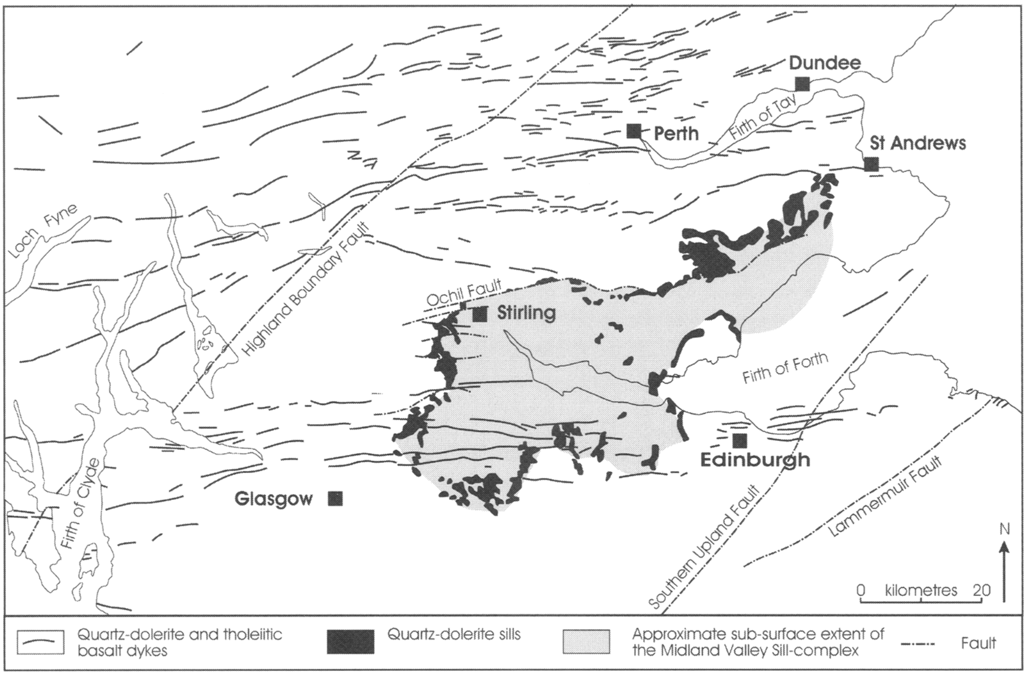

Fig. 5. Distribution of Stephanian tholeiitic dykes and sills in the Scottish Midland Valley and southern Highlands. (After Cameron & Stephenson 1985.)

SMV the dykes were partially emplaced along penecontemporaneous E–W tensional faults. Cross-cutting relationships demonstrate that dyke emplacement involved repeated pulses of magma (Stephenson 1983). The dykes average 30 m in width, but individually may reach up to 75 m (Richey 1939) and can be traced as en echelon offsets for up to 130 km. Geophysical modelling suggests that some dykes (composite bodies?) may attain widths of 1000 m or more offshore (Smythe 1994).

Associated sills include the Whin Sill-complex of northern England and the Midland Valley Sill-complex of Scotland. The latter underlies an area of about 1900 km^2 around the inner Firth of Forth, and locally has a composite thickness of *c.* 200 m and a total volume estimated at over 200 km^3 (Francis 1982) (Fig. 5). Field, petrographic and geochemical evidence indicates that the Midland Valley Sill-complex was fed by the E–W-trending dykes (Macdonald *et al.* 1981; Dunham & Strasser-King 1982; Francis 1982).

Permian volcanism

The Early Permian saw a further significant change in the tectonic forces affecting northern Britain, possibly due to the southward propagation of the Norwegian–Greenland Sea rift system (Read *et al.* 2002). These forces gave rise to NNW–SSE basins and renewed volcanism in Scotland, contemporaneous with rifting and magmatism in the central North Sea as well as in the Oslo district of Norway (Neumann *et al.* 2004).

Although many of the Permo-Triassic basins of offshore Scotland follow NE–SW trends inherited from Caledonian structures (Anderson *et al.* 1995), they are cut by NNW–SSE rift faults that provided a major control on both volcanism and sedimentation (McLean 1978). The westernmost rift, skirting the SW coast of Scotland and tangential to the Ulster coastline, contains 616 m of basaltic lavas and tuffs (Penn *et al.* 1983). Farther east, the Islay–Machrihanish–Stranraer lineament is marked onshore mainly by fault-controlled basins containing Permian sedimentary sequences. Between Islay and Jura, one such narrow half-graben includes the 120 m-thick Glas Eilean lava succession, erupted from an isolated volcano at *c.* 285 Ma (Upton *et al.* 1987). Farther NNW along the same lineament small subsilicic alkaline dykes of Permian age were intruded on Colonsay and Mull (Upton *et al.* 1998).

In the next rifted zone to the east, up to 240 m of lavas, preserved in the Mauchline, Sanquhar and Thornhill areas, include some highly silica-undersaturated basanites and olivine nephelinites (Eyles *et al.* 1949). Plant debris near the base of the sequence is consistent with an earliest Permian age (Wagner 1983). K–Ar whole-rock dates of 281–278 Ma are early Permian (De Souza 1979, 1982), and palaeomagnetic data also support a Carboniferous–Permian boundary age (Harcombe-Smee *et al.* 1996). Based on new Ar–Ar dating, Monaghan & Pringle (2004) propose that alkaline intrusions and vents, probably partly coeval with the eruptions, occurred in the period 298–292 Ma. Over 60 necks are known, mostly within a 20–30 km radius of the Mauchline Basin. Many contain wind-rounded sand grains and blocks of sandstone similar to those intercalated within the lava sequence. Intrusions within the necks are predominantly of highly silica-undersaturated foidites, lamprophyres and basaltic rocks with petrological affinities to the lavas, suggesting that they mark the eruptive sites for the Mauchline lavas (Fig. 1). Many of the major alkaline basic sills and sill-complexes in the west of the SMV are probably coeval with the Mauchline volcanic rocks (see above).

A number of relatively young sills of alkali basalt parentage occur along the NE extrapolation of the Southern Upland Fault, including that of Fidra Island to the ENE of Edinburgh (Fig. 1) (Downes *et al.* 2001), as well as several necks cut by basanitic intrusions. A recent K–Ar date (Downes *et al.* 2001) for Fidra of 264 ± 10 Ma may indicate that these intrusions signify a Permian rejuvenation of activity along this fault zone; earlier age determinations (Forsyth & Rundle 1978; McAdam & Tulloch 1985; Wallis 1989) also suggest Permian ages for magmatism in this region.

Although the principal magmatic foci in the Carboniferous and Permian lay in south and central Scotland, there are some small subvolcanic necks in the Hebrides and Scottish Highlands, filled with fragmental material and characterized by the presence of monchiquitic rocks (Rock 1983). These diatremes may owe their existence to near-surface degassing of the volatile-rich magmas that were also responsible for the late Carboniferous–Permian lamprophyric dyke swarms of the northern Highlands and Orkney (see above).

Geochemistry and petrogenesis

As noted earlier, northern Britain was experiencing extensional stresses during the Early Carboniferous (Leeder 1982; Leeder & MacMahon 1988; Read *et al.* 2002), and it is inferred that the onset of widespread and voluminous magmatism in the Dinantian was a consequence of lithospheric attenuation. Most of the subsequent late Visean–Permian activity may be attributed to smaller scale lithospheric readjustments accompanying the strike-slip faulting, permitting partial melting in the underlying mantle. The magmatism persisted intermitently over a period of 70 Ma or more.

Despite the recognition that the Burntisland and Bathgate successions can more properly be regarded as precursors to the Silesian style of magmatism, in the following section 'Dinantian' will be used in the inclusive sense in which it was employed by Macdonald (1975) and Smedley, (1986*a*, 1986*b*, 1988*a*) in the works that constitute the data source for this paper.

Although most of the transitional–strongly alkaline magmatism resulted from relatively small-degree mantle melting, the Stephanian tholeiitic magmas were clearly the product of a more profound and larger scale melting episode. There is a wide compositional overlap between the Dinantian and the Silesian–Permian basaltic rocks (Fig. 6). With the exception of the Stephanian tholeiitic magmas, there is an overall trend indicative of a general reduction in the degree of melting with time. The Stephanian activity thus stands out as a remarkable anomaly within an otherwise unified magmatic record.

Genesis of Dinantian basalt magmas

Trace-element and Sr–Nd isotopic data for the basaltic and trachybasaltic rocks imply that they were derived from heterogeneous garnet lherzolite mantle sources (Macdonald 1975, 1980; Smedley 1986*b*, 1988*a*) by partial melting (< 5%) at depths of 60–80 km. The heterogeneity is indicated by characteristic changes in the trace element and, to a lesser extent, in the Sr, Nd and Pb isotopic signatures of different areas. The incompatible element and Nd-Sr isotopic compositions of the Dinantian basalts are comparable with those of oceanic island basalts (OIB) and the regional variations observed merely mirror, on a local scale, those reported globally for OIB (Smedley 1986*a*). The variation of εNd v. εSr for the Dinantian basalts is shown in Figure 7. The data field is essentially indistinguishable from that of OIB.

The Primitive Mantle-normalized trace-element patterns of the most basic rocks (with MgO ⩾ 4%) resemble those of OIB and, together with the isotopic data, indicate minimal

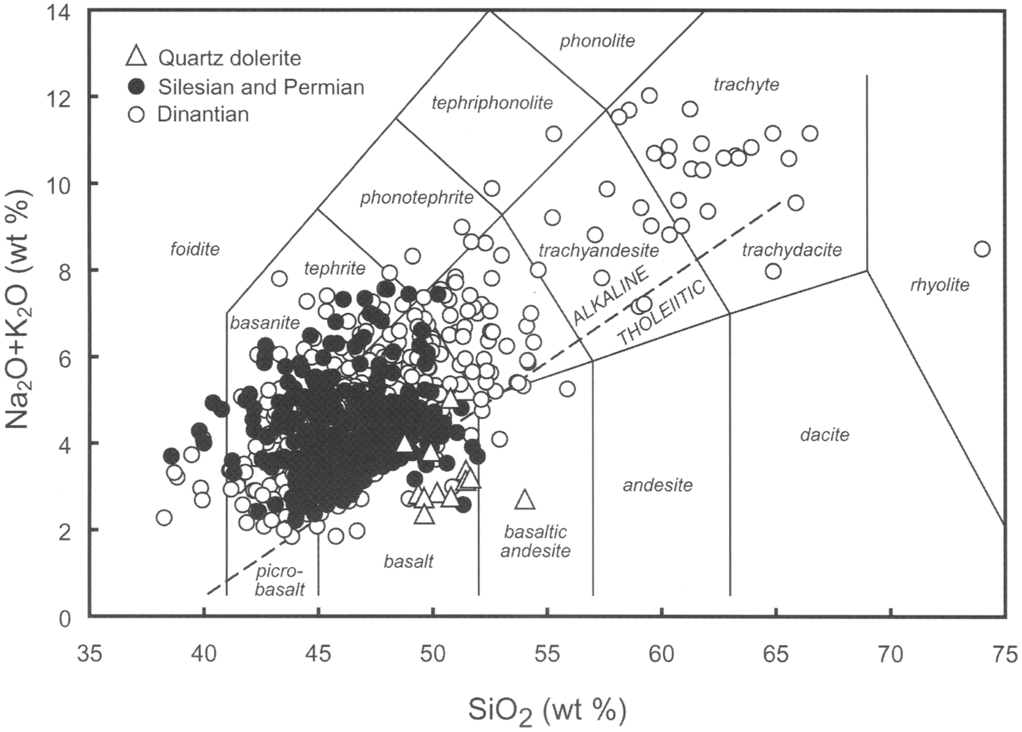

Fig. 6. Total alkali–silica diagram for Scottish Carboniferous and Permian basic igneous rocks (after Le Bas *et al.* 1986). Data from Smedley (1986*b*) and Wallis (1989). The broken line separates Hawaiian alkali–basalts and tholeiitic basalts (from MacDonald & Katsura 1964).

involvement of the continental lithosphere, suggesting an asthenospheric origin for the magmas (Fig. 8). That garnet was involved in the melt processes is evidenced by a relative depletion in Y in the normalized patterns.

Whilst certain trace-element and Sr–Nd isotope characteristics of the basic Dinantian lavas are similar to those of the earlier, late Caledonian calc-alkaline magmatism, they differ in lacking the high K, Rb and radiogenic Sr of the latter (Smedley 1986*a*, *b*). Smedley attributed this to the absence of any contribution to the Dinantian mantle sources from a relict subducted slab, indicating effective convective stirring in the mantle source in the 60–70 Ma interval between the two periods of magmatism. In a subsequent paper, Smedley (1988*b*) noted small but significant differences between the basalts from north of the Highland Boundary Fault and those from the SMV; basalts from Kintyre have slightly lower εNd and slightly higher $^{87}Sr/^{86}Sr$ ratios than those from south of the fault. She suggested that the isotopic distinction implied that the Highland mantle was slightly enriched relative to that beneath the SMV, and that there may be a lithospheric component to the magmatism north of the fault; nevertheless, she still regarded the principal magma sources as being sub-lithospheric.

Wallis (1989) also concluded that there was a lithospheric component in many of the Dinantian lavas and that they had resulted from mixing small-degree (< 3%) partial melts from the convecting asthenosphere with still smaller degree partial melts (< 1%) from the overlying lithospheric mantle in a ratio of about 9:1. Macdonald (1975) noted that particular petrographic associations could be recognized in different parts of the Dinantian lava successions and that these have distinct chemical signatures. Anomalously low concentrations of K in many of the Midland Valley basaltic lavas were attributed to a residual K-bearing phase, possibly phlogopite, in the mantle source that was only consumed during higher degrees of partial melting (Macdonald 1980; Smedley 1988*a*). The lack of notable potassium depletion, coupled with greater degrees of silica saturation in the generally more voluminous magmatism of the western Midland Valley, was taken to imply

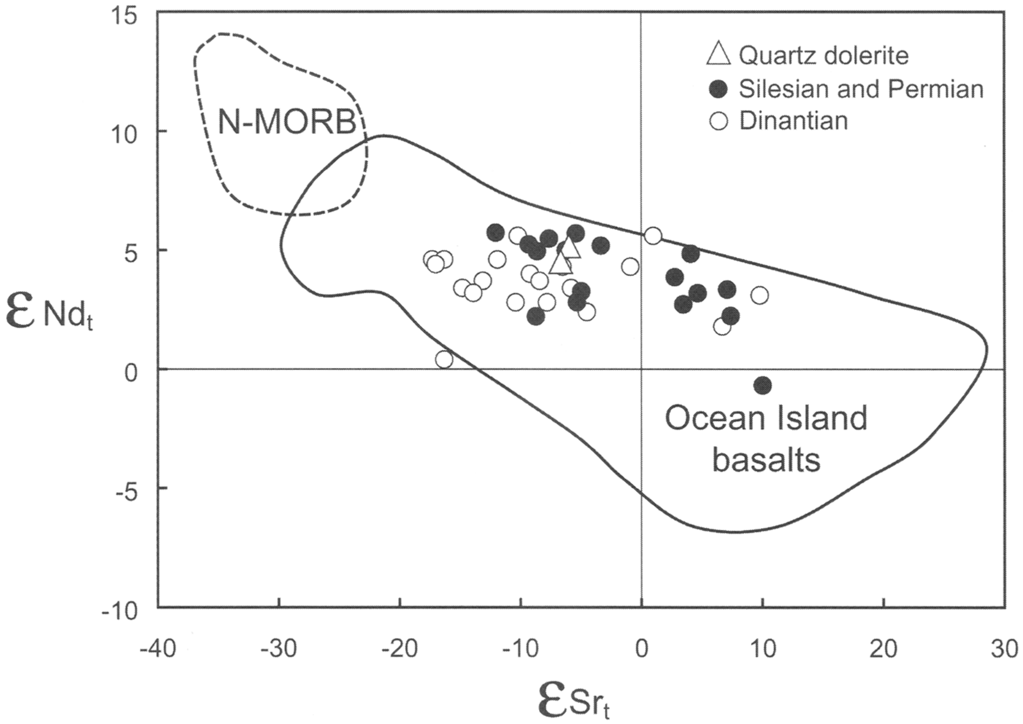

Fig. 7. εNd v. εSr for Scottish Carboniferous and Permian igneous rocks in relation to fields for OIB and N-MORB. (Data from Smedley 1986*b*; Wallis 1989: OIB and N-MORB fields from Hoffmann 1997.)

greater degrees of partial melting in the west than in the east (Wallis 1989). However, trace-element modelling of the most basic rocks showed that much of the inter-regional variation in incompatible elements could not be accounted for either by variable degrees of partial melting or by fractionation of the observed phenocryst phases. The best model involved varying degrees of partial melting superimposed on slight source-region heterogeneity (Smedley 1988*a*).

In a subsequent section describing xenoliths and megacrysts entrained in the basic rocks, evidence is presented for metasomatic enrichment of the upper mantle and lower crust beneath Scotland. It may be speculated that some of the subtle geochemical variation in the basalts reflects interaction between the predominantly asthenosphere-derived magmas and variably enriched lithospheric mantle.

Fractional crystallization of Dinantian magmas

Evolution of the primitive Dinantian basalt magmas was largely accomplished by fractional crystallization in which olivine and clinopyroxene played a dominant role. Ankaramitic lavas, containing a high modal proportion of olivine and augite phenocrysts, are commonly observed. The influence of clinopyroxene fractionation can be shown, for example, in the behaviour of Al and Ca in relation to Mg in whole-rock compositions (Macdonald 1975; MacDonald & Whyte 1981). There is an antipathetic relationship between Al_2O_3 and MgO over a range of approximately 12–4 wt% MgO in the Dinantian whole-rock compositions (Fig. 9).

Several workers (Clark 1956; Russell 1984; Smedley 1986*b*) noted the complexity of zonation in the clinopyroxene phenocrysts and inferred that the magmas had experienced polybaric fractionation histories. Russell (1984) deduced from the Al^{VI}/Al^{IV} distribution in pyroxene cores, together with the composition of their associated high-Al spinels, that crystallization commenced at pressures of up to 11.5 kbar, i.e. at subcrustal depths. It appears likely that primitive picritic magmas were arrested at, or close to, the crust–mantle boundary where they resided until fractionation of olivine (ol), clinopyroxene (cpx) and subordinate spinel (sp) had reduced the melt densities sufficiently for further crustal ascent to take place. This interpretation is supported by

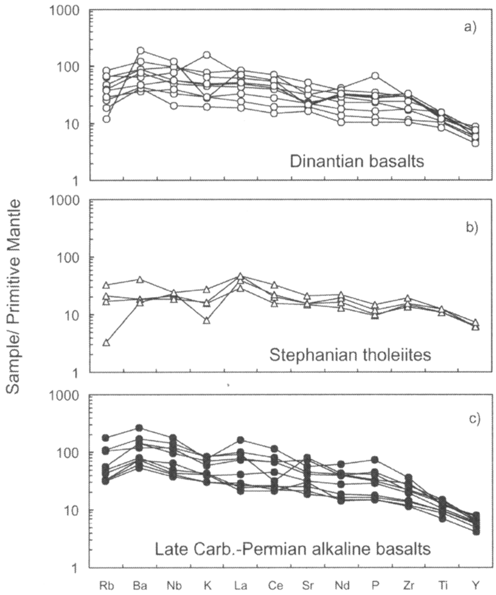

Fig. 8. Primitive Mantle-normalized trace-element plots for representative Scottish Carboniferous–Permian basic igneous rocks. (**a**) Dinantian basalts; (**b**) Stephanian tholeiitic intrusions; (**c**) Silesian–Permian alkaline basalts. Normalizing factors after Sun & McDonough (1989). Data from Smedley (1986*b*) and Wallis (1989).

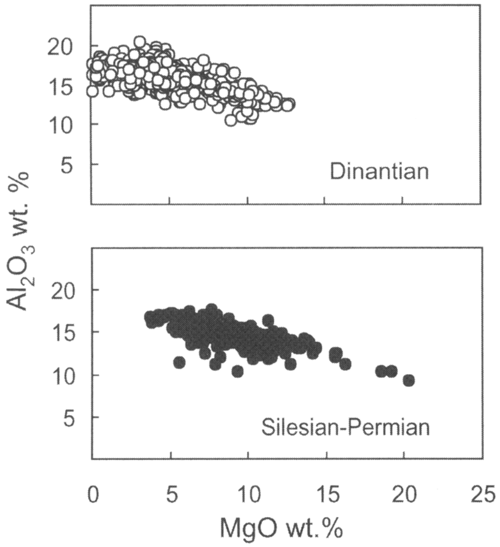

Fig. 9. Al_2O_3 v. MgO wt% variation diagram for Dinantian and Silesian–Permian volcanic rocks. (Data from Smedley 1986*b*; Wallis 1989).

the observation that primitive high-Mg melts are not represented among the Dinantian lavas and intrusions. Although some of the ol–cpx-phyric rocks have bulk MgO contents of up to 12 wt%, (Fig. 9), the groundmass compositions (taken as indicative of melt compositions) are not more magnesian than *c.* 10 wt% MgO. Accordingly, these magmas are regarded as having had significant enrichment in olivine and clinopyroxene crystals. It may be inferred that ol–cpx cumulates (wehrlites and olivine pyroxenites) and subsequent ol–cpx–pl cumulates (gabbros) were generated at depth during the interrupted ascent histories of the magmas.

The strongly porphyritic nature of many of the Dinantian extrusive and intrusive rocks, together with their broad compositional range, further indicates that magma residence in magma chambers was general and widespread. As a result of these subcrustal and crustal holding stages, the bulk of the Dinantian magmas were erupted in a relatively fractionated condition so that in some areas basaltic hawaiites and hawaiites predominate over basalts proper. Further fractional crystallization in near-surface magma chambers is suggested by hawaiitic lavas in the Renfrewshire Hills and Campsie Fells that exhibit slight variations in composition during the course of a single eruption (Kennedy 1931; MacDonald 1967; Boyd 1974).

The early–mid-Visean rocks show a compositional continuum from basalt to more silica-rich compositions (Fig. 6). The trachytes, phonolitic trachytes and (scarce) rhyolites are regarded as derivatives of prolonged fractional crystallization from the trachybasalt–trachyandesite stage of magma differentiation (Macdonald 1975). These more evolved rock types, however, lack modern study and it is reasonable to suspect that the petrogenesis of some of the more highly siliceous magmas involved varying degrees of crustal assimilation accompanying fractionation.

Late Visean, Silesian and Permian magmas

Much of the late Visean, Silesian and Permian magmatism involved ascent of silica-poor, alkalic basic magmas that were markedly more primitive than their Dinantian predecessors (Figs 6 and 9). Although, typically, the basic rocks are olivine- or olivine–augite-microphyric varieties with MgO contents >8%, some phenocryst-enriched rocks have MgO values of up to 20 wt% (Fig. 9). That the magmas were erupted in small volumes probably reflects their origin as small melt-fractions.

The absence of any significant volumes of differentiates with <3 wt% MgO is in marked contrast to the situation pertaining in the Dinantian (Fig. 9). This contrast is attributed to higher overall magma ascent rates, reflected not only in the predominance of more-primitive compositions, but also in the observation that many of the magmatic rocks carry mantle xenoliths.

Among the most primitive melts reaching near-surface levels (with >12 wt% MgO) were the Late-Permian olivine melanephelinite dykes in Orkney (Upton *et al.* 1992). In a general review of the geochemistry of the alkaline basic dykes in the Highlands and Islands, Baxter (1987) concluded that the magmas resulted from small degrees (0.5–2%) of partial melting of a chemically heterogeneous garnet lherzolite mantle source. Subsequently, a broad-scale geochemical survey of the Silesian–early Permian basic rocks of Scotland was undertaken by Wallis (1989), which showed that they present a remarkably coherent group in terms of their whole-rock chemistry (Wallis 1989) (Figs 6 and 9). Isotopic and trace-element data from this survey implied that, as with the more limited sample set investigated by Baxter (1987), the magmas originated from a very limited range of melting of a heterogeneous asthenospheric mantle source at somewhat greater depths (80–90 km) than proposed for the generation of the Dinantian magmas.

Representative Primitive Mantle-normalized incompatible trace-element patterns for selected Silesian–Permian basic rocks (MgO >4 wt%) are illustrated in Figure 8. In comparison with the Dinantian basalts, the Silesian–Permian basalts show significantly higher contents of the more incompatible elements. As in the Dinantian basalts, Y contents suggest buffering by residual garnet in the mantle source. εNd and εSr values for the Silesian–Permian basic rocks fall in essentially the same field as that for their Dinantian predecessors (Fig. 7), emphasizing their affinity with OIB-type basalts.

The Silesian–Permian basic rocks, together with those of the Dinantian, are shown on a Ce/Y v. Zr/Nb plot in Figure 10, the ratios being those of pairs of elements of contrasted compatibility. The ratios are insensitive to moderate degrees of low-pressure crystal fractionation of basaltic minerals, and their variation is taken to reflect differences in either the degree of mantle melting or in the mantle-source composition (Hardarson & Fitton 1991). Non-modal equilibrium melting curves are shown for primitive and depleted garnet lherzolite and spinel lherzolite mantle sources. Most of the data lie between the respective garnet- and spinel-facies melting curves, as would be expected for magmas originating from a melt column extending across the garnet–spinel transition (Hardarson & Fitton 1991). Figure 10 shows that virtually all data points fall within the field for OIB. Furthermore, it shows a generalized tendency for Zr/Nb to decrease (and for Ce/Y to increase) in the sequence: Stephanian tholeiitic (quartz-dolerite) intrusion through Dinantian basic lavas to the Silesian and Permian basic lavas and intrusion. This is consistent with these being products of decreasing degrees of mantle melting.

Wallis (1989) divided the late Carboniferous and Permian lavas and intrusions into two broad geochemical groups on the basis of their incompatible trace-element contents. The more enriched of these groups includes most of the Highland dykes and about half of the Fife and Lothian sills, together with the smaller basanitic intrusions associated with volcanic necks in the eastern Midland Valley. These represent the smallest degrees of partial melting and show no evidence of lithospheric contamination. The less-enriched group includes the remainder of the Fife and Lothian sills, the Ayrshire sills, the Troon lavas and most of the Mauchline lavas, deduced to have originated through larger degrees of partial melting of similar asthenospheric sources. The isotopic and incompatible element ratios of both groups suggest some interaction with lithospheric mantle material, although the overall similarity of incompatible element abundances and ratios to those of OIB indicates that contamination was minor and insufficient to affect the degree of silica-undersaturation significantly.

The geochemical provinciality observed for the Dinantian basalts appears, to some extent, to have persisted throughout the Silesian and into the Permian (Macdonald 1980; Smedley 1988*a*). Wallis (1989) concluded from trace-element modelling that these late Palaeozoic magmas resulted from mixing of melt fractions from at least two heterogeneous, phlogopite- and garnet-bearing peridotite mantle sources, noting that initial Sr and Nd isotopic ratios indicate minimal crustal contamination.

Fractional crystallization of Silesian–Permian magmas

Limited variations in major-element and compatible trace-element compositions indicate that, despite their generally high rates of ascent, the Silesian and Permian magmas did experience some polybaric fractionation of olivine ± clinopyroxene (Fig. 9). This is most likely

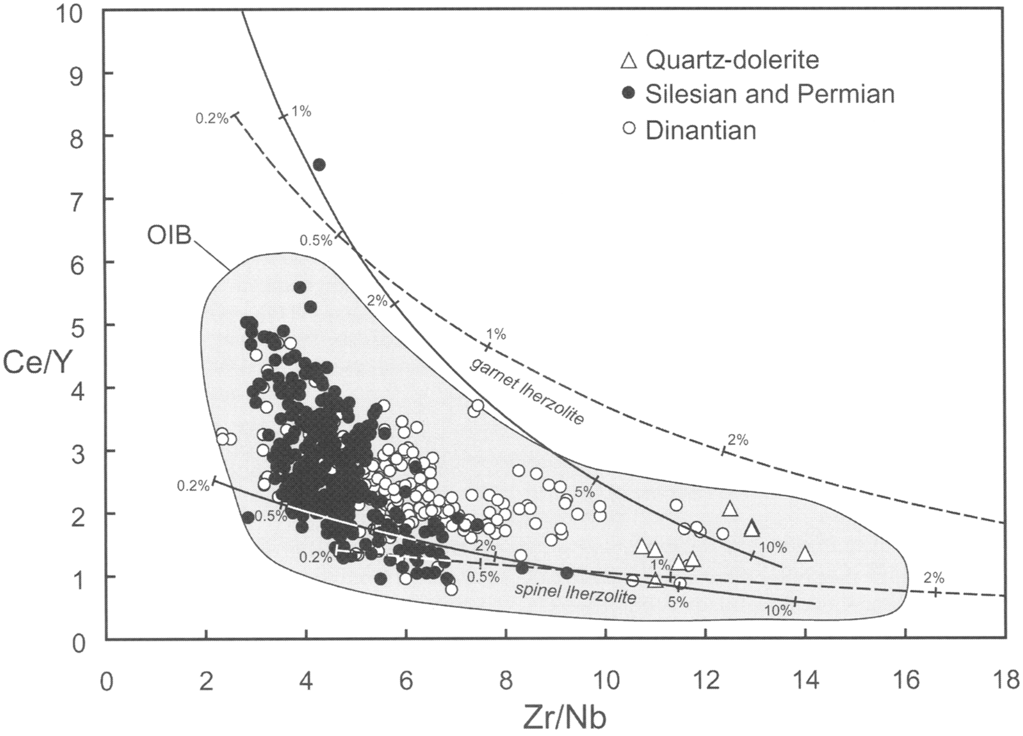

Fig. 10. Ce/Y v. Zr/Nb for Scottish Carboniferous and Permian basic (MgO > 4 wt%) igneous rocks. Non-modal equilibrium melting (Shaw 1970) curves are illustrated for a Primitive Mantle source (composition from McDonough & Sun 1995; solid curves) and for a depleted mantle source (composition calculated from the average N-MORB composition given by Sun & McDonough, 1989; dashed curves). Mantle and melting modes are from Johnson (1998). Distribution coefficients for garnet and clinopyroxene are from Johnson (1998); olivine and orthopyroxene coefficients from Bedini & Bodinier (1999); spinel coefficients from Stracke *et al.* (2003). Data from Smedley (1986*b*) and Wallis (1989). The OIB field is based on unpublished data (J. G. Fitton & D. E. James).

to have occurred during ascent, with little residence time in high-level magma chambers.

While olivine fractionation was important in the Ayrshire magmas, clinopyroxene fractionation played a predominant role in the Fife, Lothian and Highland magmas (Wallis 1989). The Al^{VI}/Al^{IV} content of some clinopyroxene phenocrysts in the Fife basanites indicates crystallization pressures as high as 20 kbar (Chapman 1976; Wallis 1989). A study of clinopyroxene crystals in the tuffs from the Elie Ness Neck (Fife) reveals a remarkable range of compositions. Variation of Al_2O_3 (1.5–11.5 wt%) and MgO (17–7.5 wt%) in these pyroxenes is ascribed to polybaric crystallization. Fractional crystallization of pyroxene (together with olivine) is inferred to have occurred at various levels in the upper lithosphere. Mixing between evolved and more primitive magma batches must have occurred. Similar conclusions were reached with respect to lavas from the Skien district, Oslofjord (Dunworth *et al.* 2001: Kirstein *et al.* 2002). The presence of olivine pyroxenite cumulates as *in-situ* products in some of the alkaline sills in the SMV is a reminder that formation of pyroxenitic cumulates was not depth restricted.

Tholeiitic magmas

Macdonald *et al.* (1981) showed that, although most of the quartz-dolerite dykes fall within a restricted compositional range (which reflects the same compositional variation observed in the Midland Valley Sill-complex), there are also slight, non-systematic trace-element variations between dykes. Some individual dykes were found to have a unique chemical ‘fingerprint’. These authors concluded that the dykes were fed, not by a single homogeneous magma, but by a number of small, partly independent, magma chambers filled by magmas derived from a heterogeneous source. Trace-element characteristics are markedly different from those of the other Carboniferous–Permian basic igneous rocks. For example, they have higher Zr/Nb ratios reflecting an origin through greater degrees of partial melting (Fig. 10). M. Howard (pers. comm. 2001) concluded, from trace-element considerations, that crustal contamination was important in the evolution of the tholeiitic magmas. Representative Primitive Mantle-normalized trace-element patterns for the Stephanian quartz-dolerites (Fig. 8) illustrate their lower contents of incompatible elements and generally flatter patterns in comparison with those of most of the Scottish Carboniferous–Permian basic rocks.

Possible mantle plume involvement

The possibility that one or more mantle plumes may have been instrumental in promoting the widespread north European Carboniferous–Permian magmatism (Neumann *et al.* 2004; Wilson *et al.* 2004) can be evaluated on the basis of the available data from the Scottish volcanic province. The Clyde Plateau eruptions followed significant regional uplift and accumulation of the lava plateaux was rapid. Such features are typical of continental flood basalt sequences associated with the rise of anomalously hot plumes from the deep mantle.

However, whereas these arguments could be used to postulate that much of the Scottish magmatism could represent an example of a (small-scale) plume-related flood basalt province, the case is not persuasive. Helium isotope data (Kirstein *et al.* 2004) provide no reason to invoke plume involvement. It is more likely that the Dinantian, together with all of the Silesian and Permian, alkali basaltic magmatism was solely due to adiabatic decompression melting of the underlying mantle during successive transtensional regimes (Smedley 1986*a*, *b*; Read *et al.* 2002). Smedley (1986*a*) considered that the compositional variation of the Dinantian basalts reflects, to some extent, the relatively rapid northward migration of the Scottish lithosphere (15° of latitude in 40 Ma) over a wide area of inhomogeneous convecting sub-lithospheric mantle. Despite the relatively long time periods involved, no hot-spot trace is discernible within the migrating plate as would be anticipated if the alkalic magmas were plume-generated.

In contrast to the deeper mantle sources postulated for the alkali basaltic magmas, the generation of the voluminous Stephanian tholeiitic basalt magmas may be attributed to larger scale and shallower melting of a more depleted mantle source (possibly mid-ocean ridge basalt (MORB)-source) well to the east of Scotland. High Ti–Fe tholeiitic magmas, which typify the Stephanian intrusions, tend to occur in regions where active lithospheric spreading is taking place due to the influence of a mantle plume (Brooks & Jakobsson 1974). Ernst & Buchan (1997) proposed that a mantle plume rising beneath the Skaggerak area, between Denmark and Norway, may have been the focus of a giant radiating dyke swarm in which the quartz-dolerite dykes and sill-complexes of northern Britain, the Oslo Rift and southern Sweden marked the arms of a ‘triple junction’. Whilst the case for involvement of a mantle plume may not be compelling for the north British Carboniferous–Permian magmatism as a whole, it may be stronger with respect to the Stephanian event. The proposition that the tholeiitic magmas were generated from mantle sources well to the east of Britain avoids the dilemma concerning the origin of the incompatible element-enriched magmas that characterized much of the early Permian volcanism across south and central Scotland. As these latter represent small melt-fractions from the mantle, the problem would have been to account for their genesis from mantle sources that should, in their recent past, have been extensively depleted by extraction of large melt-fractions during the Stephanian.

Xenoliths and megacrysts

Much information concerning the nature of the lithosphere that the Carboniferous and Permian magmas traversed en route to the surface can be gained from the wide assortment of xenoliths contained in them. The crust is believed to range from 27 to 35 km thick (Bamford *et al.* 1977). It was, specifically, the basanites, olivine nephelinites and related silica-poor alkaline mafic magmas that had the requisite ascent rates to entrain deep-sourced xenoliths. Some of these, including alkali basaltic plugs SW of the Kelso Basin (e.g. Cooms Fell) and the Heads of Ayr Neck on the west coast of the SMV (Fig. 1), are Dinantian. Comparable early Carboniferous xenolith-bearing basalts occur in England (Calton Hill, Derbyshire) and in Ireland, e.g. Croghan Hill (Upton *et al.* 1983). Most xenolith hosts are, however, of Late Carboniferous–Permian age.

In the following section the deep-sourced xenolithic materials will be discussed under four headings: (1) peridotites and garnet pyroxenites of presumed mantle origin; (2) garnet-free pyroxenitic xenoliths for which shallow-mantle or deepest crust provenances have been proposed; (3) granulite-facies meta-igneous xenoliths of lower-crustal origin; and (4) megacrysts and geochemically evolved xenoliths.

Peridotites and garnet pyroxenites

The peridotites are predominantly spinel lherzolites; harzburgite xenoliths are extremely rare. They typically exhibit granoblastic–porphyroclastic metamorphic textures and are regarded as representing a mélange of relatively refractory mantle rocks. In contrast, rare dunitic samples may represent either cumulates or metasomatic products derived from lherzolites.

Because of secondary alteration the peridotite xenoliths from most Scottish localities are unsuitable for detailed research; geochemical investigations relate to a few localities where fresh peridotites occur. The Sr and Nd isotopic signatures of the peridotite xenoliths from these localities are compatible with their having originated as fragments of variably enriched lithospheric mantle (Menzies & Halliday 1988).

The data suggest that, relative to spinel lherzolite mantle xenoliths globally, those from Fidra (on the southern coast of the Firth of Forth and on the northern fringe of the Southern Uplands Terrane) are somewhat more iron-rich. This may signify either restricted melt extraction or metasomatism prior to entrainment (Hunter *et al.* 1984). Clinopyroxene rare earth element (REE) data confirm that peridotites from Fidra have been affected by cryptic metasomatism (Downes *et al.* 2001). The major- and trace-element contents of the Fidra peridotites fall within the normal range of variation of spinel peridotites that have undergone variable depletion due to partial melting. The Sr and Nd isotopic characteristics of the Fidra samples are similar to those from the Phanerozoic parts of western Europe and were probably derived from shallow (relatively young) lithospheric mantle (Downes *et al.* 2001).

Trace-element studies of clinopyroxenes in spinel lherzolite xenoliths from localities north of the Great Glen Fault (Rinibar, South Ronaldsey, Orkney and Streap Comlaidh) indicate complex metasomatic histories for the subjacent lithospheric mantle that cannot be attributed to a homogeneous metasomatic melt or to a unique metasomatic event (Coltorti *et al.* 2003). Estimates of equilibration conditions for the Streap Comlaidh peridotites are 1100–1200 °C and 14–23 kbar (Praegel 1981). Variability in the compositions of the Scottish xenoliths may be due to enrichment events rather than to depletion, and the presence in some, of amphibole and mica is taken as evidence for modal metasomatism (Hunter & Upton 1987). Although these metasomatic events are undated it is probable, in view of evidence from the pyroxenites described below, that some were contemporaneous with the Carboniferous and Permian tectonism and magmatism. The Scottish peridotite xenoliths tend to be finer grained than most spinel lherzolite xenoliths worldwide, as well as exhibiting textural disequilibria. These features may relate to there having been insufficient time, or temperatures that were too low, to cause textural equilibration since the last (Caledonian?) deformation episodes.

Scarce garnet clinopyroxenite and garnet websterite samples occur in the Carboniferous–Permian xenolith suites (Upton *et al.* 2003) and are inferred to have equilibrated at pressures of around 20 kbar. On this assumption, equilibration temperatures for three xenoliths of 1341–1048 °C were obtained based on garnet-clinopyroxene geothermometry. Despite a wide range in Fe/Mg, similarities in their mineral Ca and trace-element contents suggest that the xenoliths are broadly cognate. They are considered to be high-pressure crystallization products of basaltic magmas, possibly related by garnet–pyroxene fractionation, occurring as subordinate intercalations within an upper mantle dominantly composed of spinel lherzolite. Discrete pyropic garnet crystals in the Elie Ness Neck in Fife have major- and trace-element characteristics indistinguishable from those of garnets from garnet pyroxenites in Ayrshire (Upton *et al.* 2003). As the Elie garnets are considered to be high-pressure phenocrysts (Chapman 1976; Upton *et al.* 2003) it could be argued that at least some of the garnet pyroxenites are deep-seated products of the Carboniferous–Permian magmatism.

Garnet-free pyroxenites and wehrlites

A very broad compositional array of clinopyroxene-rich ultramafic xenoliths occurs in the Carboniferous–Permian magmas. These include wehrlites, olivine pyroxenites, clinopyroxenites and websterites, as well as biotite and pargasite pyroxenites. With increase in modal biotite and amphibole, the latter two grade to glimmerites and hornblendites, respectively. Although many of the rocks are, like the garnet pyroxenites referred to above, metapyroxenites, others retain igneous textures and have been identified as cumulates (Chapman 1976; Upton *et al.* 2001 and references therein). In general, the werhlite–clinopyroxenite suite shows features indicating that the xenoliths originated as cpx + ol ± sp cumulates, subsequently modified texturally and compositionally to varying degrees (Hunter *et al.* 1984; Upton *et al.* 2001). The pyroxenites present evidence for multiple metasomatic events both cryptic and modal; metasomatism is deduced to have been accomplished by melts rich in Fe and Ti, as well as high field strength elements (HFSE), large ion lithophile elements (LILE), LREE and volatiles. An asthenospheric origin is proposed for these small melt-fractions that interacted with the ultramafic cumulates to produce a diverse and complexly veined assemblage of clinopyroxene- and pargasite-rich products.

In some instances pyroxenite xenoliths accompany mantle peridotite xenoliths; however, at several localities from the SMV to the Orkneys, peridotites are missing and the xenolith population is overwhelmingly pyroxenitic, although it includes lower-crustal mafic rocks. This suggests that whereas clinopyroxene-rich ultramafic rocks may, as exemplified by the garnet pyroxenites referred to above, constitute minor components within the mainly lherzolitic mantle, a layer of pyroxenitic rocks may intervene between the latter and overlying feldspathic lower crust. The wide range in modes, textures and grain sizes exhibited by the pyroxenites at individual xenolith localities is such as to imply derivation from a pyroxenitic layer of substantial thickness (Upton *et al.* 1998, 2001). While this thickness is unknown it might be reasonably speculated as being measurable in kilometres. It has been proposed that whereas wehrlites and pyroxenites are likely to be components within the peridotitic upper mantle, as well as occurring as intercalations within the metagabbroic–metadioritic lower-crustal rocks, they also constitute a distinct layer at or around Moho level. This layer may have acted as a density trap for the melts responsible for the metasomatism (Upton *et al.* 2001). As Hynes & Snyder (1995) noted that rocks of broadly mafic composition would be essentially indistinguishable seismically from peridotites at depths of 30–50 km beneath the Scottish Caledonides, the petrological Moho considered above may be indistinguishable seismically from the seismic Moho.

Pyroxenite cumulate xenoliths from several localities (e.g. Heads of Ayr and Elie Ness) appear to have contained intercumulus glass (now devitrified). This suggests that the pyroxenites were forming contemporaneously with the magmatism that led to their entrainment. Thus, although the pyroxenitic rocks at depth may have been generated over a long timescale prior to the Carboniferous (Hunter & Upton 1987), some are inferred to be cognate to the Carboniferous–Permian magmas and to be autoliths rather than xenoliths. It is also likely that at least some of the melts responsible for the metasomatism in the pyroxenitic assemblages were also late Palaeozoic.

Granulite-facies metagabbroic and metadioritic xenoliths

Xenoliths of high-grade gneissose rock principally composed of intermediate plagioclase (typically andesine) and aluminous pyroxene ('basic granulites') occur together with ultramafic rocks in many of the xenolith localities. Although garnet-bearing assemblages are extremely uncommon, symplectite textures in some of the basic gneisses from Fidra, interpreted as having grown during retrograde metamorphism of garnetiferous protoliths, suggest that the rocks experienced either uplift (depressurization) or enhanced heat flow (Hunter *et al.* 1984). Whereas there is some petrographic evidence for gradation between pyroxenites and pyroxene-rich basic gneisses, the modal subdivision between pyroxenite xenoliths and granulite-facies basic gneisses is generally so well defined as to indicate a regionally sharp boundary between the postulated pyroxenite layer and overlying basic gneisses. This may represent a 'petrological Moho' recognizable across much of Scotland.

Xenoliths of more feldspathic basic gneiss are also considered to be meta cumulates and are considered to be broadly cognate to the pyroxenitic cumulates (Halliday *et al.* 1993; Upton *et al.* 2001). The relationship between the lower crustal basic gneisses and the hypothesized underlying pyroxenitic layer may be comparable to that between the ultramafic and mafic zones of large layered complexes, but developed incrementally over very long time intervals. New magma batches from the mantle may spread out as an underplate along the petrological Moho; the latter defined by the incoming of cumulus feldspar (Cox 1980). Although such high-pressure ultramafic cumulates were forming contemporaneously with the Carboniferous–Permian magmas, no evidence of comparable 'young' feldspathic cumulates has been recognized. Nevertheless some of the metasomatic modifications identified in the basic gneisses (Upton *et al.* 2001) could, as in the case of the pyroxenites, date from these periods.

Megacrysts and geochemically evolved xenoliths

Homogeneous, high-temperature alkali feldspars (typically anorthoclases but including K-albites and sanidines) occur prominently as megacrysts up to 100 mm across in many of the xenolith localities. Some present subhedral morphologies (Chapman & Powell 1976). Associated megacrysts include kaersutite, biotite, clinopyroxene, magnetite, apatite and zircon. Oligoclasite, albitite and anorthoclasite xenoliths are also found in which the mineral species observed as megacrysts occur as accessory components. Rare magnetite–apatite (nelsonite) xenoliths are inferred to be cognate associates. These relatively exotic materials are inferred to come from veins, generally pegmatitic, within the pyroxenitic layer referred to above and to have had complex crystallization histories.

Age-dating has suggested that this megacryst–xenolith suite developed penecontemporaneously with its magmatic hosts (Macintyre *et al.* 1981). Confirmation of this conclusion comes from the observation that some megacrysts are subhedral–euhedral and clearly represent phenocrysts grown from contrasting melts coeval with the basic host magmas. Consequently, in contrast to most of the xenolithic materials described earlier, the 'geochemically evolved' xenoliths and some of the megacrysts appear to be relatively juvenile and are genetically related to the Carboniferous–Permian magmatism (Menzies & Halliday 1988).

The high alkali/calcium and high iron/magnesium character of the minerals implies crystallization from alkaline felsic (trachytic) melts (Aspen *et al.* 1990). Rare members of this xenolith suite that contain corundum (sapphire) are inferred to have crystallized from peraluminous trachytic melts. These last are also the most geochemically extreme; the presence of Nb-rich oxides (yttro-niobate, ilmenorutile and columbite) implies crystallization from Nb-rich melts that were also notably LREE-rich. The inference is that geochemically extreme melts, present in the deep crust and/or upper mantle, became intimately intermixed with the basic host magmas. The ultimate origin of these enriched melts remains enigmatic; the hypothesis that they represent highly fractionated residues from arrested basanitic, nephelinitic or lamprophyric melts is untenable as they are out of isotopic equilibrium with their hosts (Aspen *et al.* 1990). They have been attributed to asthenospherically derived carbonatitic melts, permeating and interacting with the uppermost lithospheric mantle and lowermost crust, in association with Carboniferous–Permian plate dislocations (Upton *et al.* 1999, 2001). The influence of carbonatitic fluids and melts in the metasomatism of the source of highly alkaline magmas in the Oslo Rift is noted by Neumann *et al.* (2004).

In summary, the xenolithic materials represent: (a) rock types that played an inert role in relation to the Carboniferous–Permian magmatism; (b) rocks whose metasomatism may have been, at least partly, brought about by the magmatism; and (c) some pyroxenites and also the geochemically evolved xenoliths and associated megacrysts that are deduced to have had intimate connection with the magmatism.

Summary

The Dinantian and Silesian magmatism of Scotland appears to have been triggered in response to phases of regional lithospheric extension. The most primitive mafic magmas are predominantly alkaline, with trace-element and Sr–Nd isotopic characteristics similar to those of OIB. A heterogeneous asthenospheric mantle source is indicated with partial melting occurring across the spinel–garnet lherzolite-facies transition; locally, the ascending magmas may have interacted with (and metasomatized) the lithospheric mantle. A short-lived tholeiitic magmatic event in the latest Stephanian has a different origin (higher degrees of melting of a more depleted mantle source). With the possible exception of this tholeiitic 'event', there is no strong supporting evidence for the involvement of a mantle plume in the petrogenesis of the magmas.

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