Chapter 8 Late Silurian and Devonian granitic intrusions of Scotland

Introduction

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The late stages of the Caledonian Orogeny (*c.* 430–390 Ma) saw widespread voluminous granitic magmatism of essentially calc-alkaline characteristics in the Caledonian–Appalachian mountain belt. In Newfoundland, late Silurian pluton emplacement marks the final stages of collision between Laurentia and Avalonia (Bevier and Whalen, 1990; Whalen *et al.,* 1992). A similar event is manifest in the Greenland–Scottish sector. Within Scotland, the Caledonian Igneous Province encompasses both the orthotectonic zone from Shetland to the Highland Border and the paratectonic slate belt of the Midland Valley and Southern Uplands. The Scottish late Caledonian 'Newer Granites' (*sensu* Read, 1961), the principal subject of this chapter, are most abundant in the orthotectonic zone. With the possible exception of a few lamprophyre intrusions, e.g. on Iona (Rock and Hunter, 1987), and a few alkaline dykes described in Chapter 7, Caledonian magmatism extends little beyond the orogenic front into the Foreland (Figure 8.1). The late Silurian to Early Devonian magmatism post-dates the tectono-metamorphic event associated with the oblique convergence of Laurentia and Baltica and the closure of the northern Iapetus Ocean along the Iapetus Suture (Soper *et al.,* 1992). It spans the period of late orogenic uplift and extensional collapse (Watson, 1984), and coincides with the cessation of major sinistral strike-slip along the orogenic margin. There is some evidence in Scotland, however, for late Early Devonian (Acadian') reactivation and contemporaneous magmatic activity (cf. Hutton and McErlean, 1991; Soper *et al.,* 1992), more commonly manifest in the slate belts of northern England (see Chapter 4).

Siluro-Devonian magmatism in Scotland, encompasing plutonic bodies, attendant dyke-swarms and volcanic rocks, is represented by predominantly high-K calc-alkaline rocks, and some have shoshonitic (high-K and high-Mg) affinities (Simpson *et al.,* 1979; Halliday, 1984; Stephens and Halliday, 1984; Plant, 1986). There is a significant background input of mantle-derived magmas, e.g. calc-alkaline lamprophyre and appinite suite intrusions. Although the plutons have historically been referred to as 'granites' they include a wide range of rock types from diorite through to monzogranite, with granodiorite predominant overall. These are derived mainly from a lower crustal source with some mantle component, and exhibit essentially 'I-type' characteristics (*sensu* Chappell and White, 1992), locally transitional to more alkaline 'A-type' in more evolved intrusions, e.g. Cairngorm. The chemistries of the Galloway Suite plutons within the Southern Uplands, e.g. Fleet, Criffel and Cheviot, bear some resemblance to the granites of the Lake District (see Chapter 4). Their weakly negative ■Nd, high $\delta^{18}O$ and ■Sr (Halliday, 1984) are comparable to patterns from the flysch sediments in the local Lower Palaeozoic sequences, and this argues in favour of an 'S-type' origin (*sensu* Chappell and White, 1992) through melting of this thickened young crust. (See the introduction to the Lotus quarries to Drungans Burn GCR site report for a full discussion of I-type and S-type characteristics.)

Stephens and Halliday (1984) divided the late Caledonian granites of the Grampian Highlands, Midland Valley and Southern Uplands terranes on geochemical and isotopic criteria into three suites: Argyll, Cairngorm and South of Scotland. This usefully demonstrates petrochemical provincialism within the orogen. The plutons of the Argyll Suite, and those within the Northern Highlands Terrane, map out an unusual granitic province with high Ba and high Sr characteristics and older crustal Nd signatures (Halliday, 1984; Stephens and Halliday, 1984; Thirlwall, 1989; Tarney and Jones, 1994). Intrusions of the South of Scotland and Cairngorm suites share relatively low Ba and low Sr characteristics (cf. Tarney and Jones, 1994), more typical of Palaeozoic magmatism worldwide. Tarney and Jones (1994) argue that these characteristics are derived from the subcontinental lithospheric mantle (SCLM) component rather than the continental crust. This suggests a significant change in the characteristics of the lithbspheric mantle below the orthotectonic zone. Canning *et al.* (1996), from a study of geochemical differences within late Caledonian minette dykes, argue that the boundary between these mantle provinces coincides with the Great Glen Fault. However, the changes in chemistry and isotopic signatures of the plutonic rocks occur at the NE-trending 'mid-Grampian line' of Halliday (1984), within the Grampian Terrane and some 50 km to the SE of the Great Glen Fault. Our present understanding of the history of the Great Glen Fault would argue against any major significance of this structure as a terrane boundary or re-activated older structure (Soper *et al.,* 1992; Stewart *et al.,* 1997). Similarly, there are no significant changes across any of the other major transcur-rent shears, e.g. Highland Boundary and Southern Upland faults, suggesting that the tectonic blocks south of the mid-Grampian Line all have a similar SCLM.

Plutons within the orthotectonic Highland terranes present the widest range of ages (425–395 Ma) and emplacement levels seen in the orogen, from subvolcanic, e.g. Etive, Ben Nevis, through to mid-crustal *c.* 14 km, e.g. Strontian, Foyers, Findhorn. Some of the larger plutonic bodies, e.g. Etive and Strontian, consist of several intrusions with differing source components, emplaced at different crustal levels at resolvably different times. South of the Highland Boundary Fault, pluton emplacement is upper crustal, within the Palaeozoic sedimentary pile. It is clear that the major NE-trending fault shears throughout the orogen, but particularly within the orthotectonic zone, acted as magma conduits (Watson, 1984) and controlled pluton emplacement kinematics (Hutton, 1987, 1988a; Leake, 1990).

The period of magma generation is contemporaneous with rapid crustal uplift, erosion and development of flanking molasse basins, and this complex inter-relationship is well demonstrated in the Grampian Highlands. Here, mid-crustal *c.* 415 Ma plutons, e.g. Foyers and Findhorn, emplaced at depths of *c.* 12–14 km (Tyler and Ashworth, 1983), were unroofed by the time of deposition of the Middle Devonian piedmont sediments in the Great Glen area. In Glen Coe, clasts of granodiorite and microdiorite within Lower Devonian conglomerates, point to unroofing pre-dating volcanicity and the intrusion of the Etive pluton at *c.* 400–395 Ma (Bailey, 1960; Kynaston and Hill, 1908).

The suites identified by Stephens and Halliday (1984) provide a classification scheme independent of differences in granitic type or structural environment. Subsequently, data has become available for many more intrusions (such as in the NE Grampian Highlands) and the scheme is open to some modification on the basis of work by Tarney and Jones (1994). Hence, although the scheme is adopted here in broad terms, there are some groups of intrusions that are classified differently in Stephens and Halliday (1984), in Stephenson and Gould (1995) and in this volume. The Argyll Suite has been expanded to include the calk-alkaline plutons of the Northern Highlands. It is recognized, however, that some Northern Highland plutons are in part transitional into the slightly older alkaline suite described in Chapter 7 (cf. Fowler and Henney, 1996). The slightly younger plutons of the Southern Uplands, which have 'S-type' characteristics (Fleet, Criffel and Cheviot) were excluded from the scheme of Stephens and Halliday (1984) and are referred to here as the Galloway Suite.

Argyll and Northern Highlands Suite

This suite includes all late Caledonian plutons from the Grampian Highlands NW of the geochemically defined 'mid-Grampian Line' and from the Northern Highlands (Figure 8.1). With restoration of movement along the Great Glen Fault of *c.* 105 km, the suite defines a NE-trending belt some 60 km wide. The suite comprises predominantly hornblende-biotite granodiorite and biotite granodiorite plutons, with relatively minor diorite (some appinitic) and monzo-granitic components. The plutons are strongly metaluminous ($CaO + Na_2O + K_2O > A1_2O_3 > Na_2O + K_2O$) with high Na, Sr and Ba and low Th, Nb and Rb. All have characteristically very low ■Nd values, –10 to +3, generally high ■Sr, –7 to +58 and $\delta^{18}O$ values in the range 7.2 to 10.7 ‰ (Halliday, 1984). Towards the western margin of the belt, the Ratagain intrusion has some elemental characteristics transitional between metaluminous cafe-alkaline rocks and the alkaline rocks of the NW Scottish Highlands (see Chapter 7), e.g. very high Ba and Sr.

The Lochaber District, SE of the Great Glen Fault, is one of the few areas within the Caledonian Igneous Province, where extrusive products may be demonstrably linked to high-level plutons. Intrusive rocks at Ben Nevis and Glen Coe represent early phises of pluton emplacement into collapsing caldera systems. The Ben Nevis and Allt a' Mhuilluin GCR site (Chapter 9) provides evidence for high-level pluton emplacement and the derivation, in part, of the overlying volcanic pile from the underlying granitic magma body. While the availability of granitic magma during cauldron subsidence along a series of ring fractures beneath the Glen Coe centre is demonstrated within the Stob Mhic Mhartuin and Loch Achtriochtan GCR sites (Chapter 9), this magma is not related to that of the preceding volcanic rocks. The Etive pluton represents the final stages of significant magma intrusion in the Lochaber area at *c.* 400 Ma. Here, the Cruachan Reservoir GCR site demonstrates a ring-fracture system, and drop-down of a caldera fragment, subsequently exploited as a magma conduit by the Quarry Intrusion. The Bonawe to Cadderlie Burn GCR site is an instructive cross section through the multiple pulse main granodioritic-monzodioritic fades of the pluton. Assimilation of country rock enclaves and mingling of contemporaneous basic magma, are a feature of both sites. At the time of writing the GCR review did not include plutons from SE of the Great Glen Fault emplaced at mid-crustal levels between 10 and 14 km, for example Allt Crom (Key *et* al., 1997), Ballachulish (Pattison and Harte, 1985; Weiss and Troll, 1989), Corrieyairack (Key *et* al., 1997), Findhorn (Piasecki, 1975), Foyers (Marston, 1971), Rannoch Moor (Leighton, 1985) and Strath Ossian (Clayburn, 1981).

North of the Great Glen Fault, the GCR sites largely reveal aspects of deeper emplacement levels within the Proterozoic crust. Plutons such as Strontian, Ratagain and Rogart are composite intrusions, with basic, granodioritic and granitic magma components derived from differing source regions. Together with the Ross of Mull pluton, they demonstrate the availability of contemporaneous hydrated basic magma during emplacement. Within the Loch Sunart GCR site, shoshonitic meladiorites and mafic-rich enclaves are present in all fades of the Strontian pluton. The mafic enclaves here and in the Glen More and Loch Airighe Bheg GCR sites of the Ratagain and Rogart plutons probably represent disrupted synpiutonic dykes. Within the central region of the Ross of Mull pluton a wide range of hybrid rocks are found in the Knockvologan to Eilean a' Chalmain GCR site. These are testament to mixing and mingling of the basic and granodioritic magmas, and give rise to an apparent reverse zonation within the pluton. The Cnoc Mor to Rubh Ardalanish GCR site contains examples of granitic hybrid rocks derived from the assimilation of country rock material. Isotopic studies of many of these intrusions consistently identify both crustal and mantle signatures in the main pluton facies (Halliday *et al.,* 1984). A subcontinental lithospheric mantle source is favoured for the basic enclaves (cf. Holden *et al.,* 1991) and the syenitic component of the Ratagain pluton (Thompson and Fowler, 1986).

High-temperature shear and magmatic state deformational fabrics are common features of the mid-crustal Argyll and Northern Highlands Suite intrusions from both sides of the Great Glen Fault. The Loch Sunart, Glen More and Loch Airighe Bheg GCR sites, within the Strontian, Ratagain and Rogart plutons respectively, provide fine examples of this emplacement deformation (Hutton, 1988b; Hutton *et al.,* 1993; Hutton and McErlean, 1991; Soper, 1963). In the high-level plutons SE of the fault, these fabrics are present but less distinctive, e.g. the Bonawe to Cadderlie Burn GCR site of the Etive pluton. These most likely derive from deformation within the linked NE–SW shear fracture systems during the waning stages of Caledonian deformation within the Northern Highlands and Grampian Highlands terranes.

Cairngorm Suite

At the time of writing, the GCR did not include examples from this important suite of intrusions, but for completeness a brief description is given here. The Cairngorm Suite, consists of late Caledonian (*c.* 400 Ma) voluminous granitic plutons, occurring within the northern Grampian Highlands (Figure 8.1). A large gravity low extends between the Monadhliath and Mount Battock masses. This suggests the presence of substantial volumes of low density rocks in the crust (Rollin, 1984), forming an easterly trending batholith at depth (the East Grampian Batholith of Plant *et al.,* 1990). The granite masses at the surface probably represent cupolas (Cornwell and McDonald, 1994). Aeromagnetic anomalies, commonly annular in form, e.g. at Cairngorm and Lochnagar, suggest the presence of magnetic lithologies. These may be either mafic-rich cumulates at depth (Brown and Locke, 1979) or magnetic rocks within the plutons not seen at the surface (Cornwell and McDonald, 1994). The plutons probably represent high emplacement levels, *c.* 5–8 km (Harrison and Hutchinson, 1987).

The intrusions comprise mainly biotite monzogranite, such as Monadhliath (Highton, 1998), Cairngorm (Harrison, 1986), Mount Battock (Webb and Brown, 1984b), Lochnagar (Oldershaw, 1974; Rennie, 1983), Ballater (Webb and Brown, 1984b), with minor granodiorite, but include a wide range of primary textural variants from micrgranite to coarse-grained, K-feldspar megacrystic granite. Secondary magmatic textures, such as xenocrystic aplitic microgranites, pegmatites and vuggy cavities (often mineral lined), are a consequence of either volatile fluxing, pressure quenching or fluidization in the plutons (Highton, 1999). High temperature late magmatic hydrothermal alteration is often extensive, e.g. Cairngorm and Mount Battock (Harrison, 1986, 1987a).

Intrusions within the suite are largely 'I-type' (^{87}Sr/^{86}Sr ~ 0.706), highly evolved, and quite distinct from the other suites, with low Ti, P, Ba, Sr and IC/Rb, and high Rb, Nb, Th and U. The isotopic signatures bear some similarity to the Argyll Suite, having low ■Nd values, –8 to –1, generally high ■Sr, +24 to +33 and δ^{18}O values of *c.* 8.2 to 11.1 ‰ (Halliday, 1984; Stephens and Halliday, 1984). The origins of this Cairngorm Suite are problematical, with the large volume granite plutons that comprise the East Grampian Batholith having highly evolved characteristics more typical of Sn-U granites (Plant *et* al., 1990). Most are high heat-producing granites, e.g. Monadhliath and Cairngorm, and coincide with thermal anomalies in the crust (Webb and Brown, 1984b; Atherton and Plant, 1985). Some plutons show transitional 'A-type' characteristics, with moderate enrichments in B, Nb, F, Li, Sn and W, e.g. Cairngorm (O'Brien, 1985; Harrison, 1986, 1987a) and Monadhliath (Highton, 1999). This is more likely a reflection of the highly evolved nature of these granites, rather than having a genetic significance. With the exception of Glen Gairn/Coilacreich (Webb *et al.,* 1992) most lack significant metalliferous mineralization.

South of Scotland Suite

This suite encompasses all remaining Siluro-Devonian plutons intruded into the Neopro-terozoic crust SE of the 'mid-Grampian Line' and the Palaeozoic sequences of the Midland Valley and Southern Uplands. Most plutons of this suite within the Grampian Highlands terrane have been termed the 'South Grampians Suite' by Stephenson and Gould (1995). The suite may also include a group of diorite-granodiorite plutons of central Aberdeenshire that pre-date the Cairngorm Suite and have been assigned by Gould (1997) to a separate 'Crathes Suite', e.g. Crathes, Balblair and Torphins.

The intrusions in the Grampian Highlands Terrane, like those of the Argyll and Northern Highlands Suite, have close spatial associations with major NE-trending shear faults such as the Loch Tay and Glen Fyne faults, e.g. the Glen Tilt and Garabal Hill-Glen Fyne plutons. Most are composite multiple-pulse intrusions often dominated by granodiorite and moderately evolved monzogranites, but with significant gabbroic and pyroxene meladiorite (appinitic) facies rocks. Characteristically, they are strongly metaluminous ($CaO + Na_2O + K_2O > A1_2O_3 > Na_2O + K_2O$) with relatively higher K and Th, but lower Zr, La, Ce, Ba, Sr and Rb than the Argyll and Northern Highlands Suite intrusions. The transition element values in the basic to intermediate rocks, in particular V and Cr, are also commonly higher than in the Argyll and Northern Highlands Suite. All granodioritic components have low ■Nd values, –6 to –1, generally high ■Sr, +1 to +54 and $\delta^{18}O$ values of 7.5 to 10.5‰ (Halliday, 1984; Stephens and Halliday, 1984). All lack an inherited zircon component.

The depth and/or mode of emplacement of many intrusions is little documented. However, one of the finest examples of a high-grade contact metamorphic aureole within the Caledonian Igneous Province is found adjacent to the chilled margin of the Comrie pluton within the Craig More GCR site, indicating high T-low P emplacement conditions of *c.* 750°C and 2.5 kbar (Pattison and Tracy, 1991; Pattison and Harte, 1985). Comparable emplacement parameters have been obtained from the aureoles of quartz-diorite intrusions adjacent to, but pre-dating the Lochnagar pluton of the Cairngorm Suite (Goodman and Lappin, 1996).

Representative intrusions of this suite chosen for the GCR are the Glen Tilt, Garabal Hill–Glen Fyne, Glen Doll and Comrie plutons from the Grampian Highlands Terrane, together with Loch Doon from the Southern Uplands. Their designated GCR sites provide details of pluton construction rarely seen in other Caledonian intrusions, and the Forest Lodge GCR site in Glen Tilt is of international historical importance, as it was here in 1785 that James Hutton demonstrated the magmatic origin of granite. These are compositionally diverse (ultramafic to monzogranitic), zoned multiple pulse plutons, consisting of an early appinitic diorite and later granodiorite or monzogranite facies. The basic parts of these intrusions have historically attracted much attention and pioneering petrochemical research (Deer, 1938a, b, 1950, 1953; Nockolds, 1941; Nockolds and Mitchell, 1948).

The classical study by Nockolds (1941) of the Garabal Hill–Glen Fyne pluton (see below) brought to prominence the concept of zoned granitic bodies evolving through differentiation by fractional crystallization from a dioritic parental magma. Within the Garabal Hill to Lochan Dubh-Uisge GCR site, the granodioritic rocks were considered to be differentiates from a parental pyroxene-mica diorite magma, while the basic components represented crystal cumulates. Although now considered too simplistic, this model was to drive most early petrochemical studies of granite plutons worldwide. More recent interpretations point to different sources for the basic and granodioritic components. The predominantly dioritic Comrie pluton is compositionally zoned. Heterogeneities and merging contacts within the Funtullich GCR site, argue for multiple pulse injection and penecontemporaneous inward crystal accretion. The later microgranite facies, like many core facies, is highly evolved and unrelated to the earlier diorite-granodiorite facies. The Red Craig GCR site provides a fine example of wall-rock interaction and contamination at the SE margin of the predominantly dioritic Glen Doll intrusion.

The Loch Dee GCR site represents the Loch Doon pluton, which is the largest of the South of Scotland Suite plutons and was the first pluton to be defined by the Geological Survey. The pluton is the finest example within the Caledonian Igneous Province of a compositionally zoned intrusion, from a margin of pyroxene-mica diorite through granodiorite to central monzogranite. Some smaller intrusions within the Southern Uplands share these characteristics, for example Cairnsmore of Cairsphairn (Deer, 1935; Tindle *et al.,* 1988) Portencorkrie (Stone, 1995), Cairngarroch (Allen *et al.,* 1981), Priestlaw (Shand, 1989) and Cockburn Law (Shand, 1989). Other intrusions, e.g. Broad Law, Spango, Glenluce, Bengairn and Kirkowan, are single-component intrusions or show only minor compositional variation. The diorite-granodiorite Distinkhorn pluton, dated at 412 ± 5 Ma (Thirlwall, 1988), and small satellite bodies at Hart Hill, Glen Garr and Tincorn Hill are the only significant intrusions found within the Midland Valley Terrane. These and minor diorite stocks at Fore Burn close to the Southern Upland Fault, at Lyne Water in the Pentland Hills, and in the western Ochil Hills, intrude and hornfels the Lower Old Red Sandstone sedimentary rocks and lavas.

Galloway Suite

This group of intrusions consists of the Fleet, Crifell and Cheviot plutons and smaller intrusions at Portencorkrie (Stone, 1995) and Kirkmabreck (Blyth, 1955). They are younger than those of the South of Scotland Suite (Thirlwall, 1988) and have a close affinity with intrusions of the Lake District and south-east Ireland. The north-western limit of these intrusions is marked by the NE-trending Moniaive Shear zone. This structure coincides with a major geophysical discontinuity in the subcontinental lithospheric mantle and lower crustal rocks beneath the Southern Uplands (Kimbell and Stone, 1995). A basement discontinuity is also suggested by a marked contrast in the isotopic characteristics of intrusions on either side of the shear zone (Shand, 1989; Thirlwall, 1989). The inception and propogation of the shear zone through the Palaeozoic cover, during early Wenlock times, is thought to reflect re-activation of the basement discontinuity (Stone *et* at, 1997).

All of the plutons include members with S-type peraluminous characteristics ($A1_2O_3$ > CaO + Na_2O + K_2O) which are usually two-mica granites. $^{87}Sr/^{86}Sr$ ratios are typically 0.705 to 0.707, with $\delta^{18}O$ values in the range 8 to 12%o, while ■Nd values suggest derivation from Silurian turbiditic sedimentary sequences (Halliday *et al.,* 1980; Halliday, 1984). The generation of these magmas was probably a consequence of underthrusting of the Southern Uplands by the leading edge of the Eastern Avalonia continent, a view supported by Pb isotope data (Thirlwall, 1989).

The Fleet pluton is the youngest, at *c.* 390 Ma, and the most evolved of these Southern Upland intrusions. The less evolved outer pophyritic biotite granite facies of the Clatteringshaws Dam Quarry GCR site passes inwards into a weakly porphyritic biotite-muscovite granite. The garnet-bearing aphyric muscovite microgranite core facies of the Lea Larks GCR site is the most highly evolved of the Scottish late Caledonian granites. Variations in the orientation of a weak to moderately developed ductile fabric argues for intrusion during sinistral movement on the Moniaive Shear zone. The zoned Criffel pluton has played an important role in the modelling of pluton emplacement and magma chamber dynamics. Both diapirism and stoping have been proposed by different investigators and much of the crucial evidence is displayed in the country rocks and outer granodiorite facies of the Millour and Airdrie Hill GCR site. The pluton has an unusual compositional make-up, being concentrically zoned from a metalumi-nous 'I-type' outer facies to a core with peralu-minous 'S-type' characteristics. This is a unique example, not only within the Caledonian Igneous Province, and must invoke open-system multiple injection from differing sources. This paradox is well illustrated in the traverse through the Lotus Hill to Drungans GCR site.

The monzogranites of the Cheviot pluton (Carruthers *et al.,* 1932; Jhingran, 1942) are of similar age to the Cheviot lavas at *c.* 396 Ma (Thirlwall, 1988) and are considered to be co-magmatic with them (Thirlwall, 1979).

Shetland Suite

The Shetland plutons, not yet represented in the GCR at the time of writing, are divisible into eastern and western 'suites' separated by the Walls Boundary Fault (Flinn, 1988 and references therein). The timing of their emplacement is generally poorly constrained, with only K/Ar mineral ages reported.

The apparently older (*c.* 400 Ma) eastern suite, including the Graven, Brae and Aith-Spiggie complexes and the Hildesay Granite, mostly comprise granodiorite-dominated intrusions with diorite, appinitic diorite and minor basic components. The epidote-bearing main granodiorite facies of the Aith-Spiggie complex (Flinn, 1988) is unusual, although this may merely reflect late-magmatic alteration. All members of the 'suite' have geochemical characteristics similar to plutons of the Argyll and Northern Highlands Suite in the orthotectonic zone of the mainland (M. P. Atherton and coworkers, pers. comm., 1997). The minor intrusions to the east of the Walls Boundary Fault (predominatly microdiorites and calc-alkaline lamprophyres, with some porphyritic microgranodiorites) fall into two 'suites', late-tectonothermal and post-tectonic. The former are consistently foliated, with metamorphic mineral assemblages, and pre-date the plutonic complexes. The latter are generally synplutonic and are rarely deformed (Mykura, 1976).

To the west of the Walls Boundary Fault the plutonic complexes appear to be younger, with reported K/Ar ages in the range 370–360 Ma. This western suite is dominated by the Northmaven complex (Miller and Flinn, 1966; Mykura and Phemister, 1976; Phemister, 1979) and the Sandsting complex (Mykura and Phemister, 1976). These complexes are a mixture of granophyre and granite plutons (e.g. Ronas Hill, Muckle Roe and Sandsting) with some hornblende-bearing plutons (for example Mangaster Voe). Hybridization through intermingling of basic and acid components is common. All are characteristically low Ba and Sr intrusions (M. P. Atherton and co-workers, pers. comm., 1997). The Sandsting complex clearly cuts and hornfelses Middle Devonian sedimentary rocks of the Walls Formation and is closely associated in space and time with a late phase of compressive deformation and metamorphism (see the Ness of Clousta to The Brigs GCR site report, Chapter 9). This Mid- to Late Devonian deformation, which post-dates the main extensional event(s) responsible for the development of the Orcadian Basin, was probably the last phase of Caledonian folding in Britain. Both complexes are cut by zones of shearing, fracturing and hydrothermal alteration (including scapolitization and zeolitization) associated with the Walls Boundary Fault.

Appinite Suite

Appinites and their Northern Highland equivalents, the Ach'uaine Hybrids, are probably the most enigmatic intrusions within the Caledonian Igneous Province (Read, 1961; Wright and Bowes, 1979; Hamidullah and Bowes, 1987). The Ardsheal Hill and Peninsula GCR site is the type locality for 'appinites', described by Bailey and Maufe (1916) as medium- to coarse-grained rocks with essential prismatic hornblende in a groundmass of sodic plagioclase, K-feldspar and quartz. These, Bailey and Maufe (1916) and Bailey (1960) regarded as the plutonic equivalents of the hornblende-bearing lamprophyres – spessartites and vogesites; a view confirmed by more recent geochemical studies of lamprophyres and subvolcanic vents in the Southern Uplands (Rock *et* al., 1986a; Henney, 1991). However, the term Appinite Suite has become a miscellaneous term for intrusions with a heterogeneous range of ultramafic (e.g. olivine-pyroxene hornblendite), melanocratic basic and intermediate (such as olivine mon-zonite), dioritic and granodioritic rocks. Most are shoshonitic in affinity and probably of mantle derivation (Fowler, 1988a; Henney, 1991; Fowler and Henney, 1996), with elevated Sr, Ba, Ni, Cr and light rare earth elements (LREE). Appinitic intrusions have a wide distribution throughout the Scottish and Irish Caledonian Igneous Province, and typically have a close spatial relationship with the late Caledonian granitic plutons. More significant, however, is a clustering close to major faults or concentration along NW-trending lineaments (cf. Fowler, 1988b). Deeper-level intrusions often carry fabrics indicative of emplacement into a ductile shear-dominated environment (Phillips and May, 1996), although some deeper-level intrusions with breccias are known (Peacock *et al.,* 1992; May and Highton, 1997).

Invariably appinitic intrusions pre-date, or are in part contemporaneous with the late Caledonian granitic plutons, e.g. the Ballachulish, Garabal Hill and Arrochar plutons, and they have comparable emplacements ages of *c.* 430–425 Ma (Rogers and Dunning, 1991). However, they only rarely form a significant proportion of the xenolith population in such plutons, for example at Corrieyairack (Key *et al.,* 1997), Ratagain and Rogart. Appinitic intrusions were commonly preceded by breccia pipes, and acted as open-system feeders within the subvolcanic systems (Wright and Bowes, 1968; Rock *et al.,* 1986a; Platten, 1982; Henney, 1991). Numerous and varied individual intrusions occur within the Ardsheal Hill and Peninsula GCR site, where breccia pipes are intimately associated with and commonly infiltrated by both primitive and evolved magmas. A detailed example at the Kentallen GCR site illustrates the relationships between various late Caledonian events, involving an appinitic intrusion (the type 'kentallenite'), the Ballachulish pluton, several dyke sets, hydrothermal veins and faulting associated with the Great Glen Fault.

In the Northern Highlands Terrane, the Ach'uaine Hybrid intrusions of Sutherland (Read *et al.,* 1925) are a similar heterogeneous suite, predominantly of appinitic meladiorites, but ranging from ultrabasic and basic rocks through to syenite and granite. These occur as enclaves and intrusions within and peripheral to the Ratagain and Rogart plutons with good examples in the Glen More and Loch Airighe Bheg GCR sites, respectively. These appinitic rocks present evidence for the mingling of mantle-derived lamprophyric and contemporaneous syenitic magmas (Fowler and Henney, 1996).

Minor intrusions

Compositionally and temporally diverse suites of predominantly calc-alkaline, and shoshonitic minor intrusions are present in all terranes (Richey, 1938; Sabine, 1953; Smith, 1979; Cameron and Stephenson, 1985; Barnes *et al.,* 1986; Rock *et al.,* 1988; Henney, 1991; Swarbrick, 1992; Stephenson and Gould, 1995). Emplacement is clearly episodic, with several syn- to late-orogenic regional suites. Many are genetically related to individual plutons or acted as feeders for extrusive rocks. Others, particularly the calc-alkaline lamprophyres, simply reflect the regional background magmatism within the province (Rock *et al.,* 1988). Minor intrusions are a feature of many of the GCR sites described in this chapter and in Chapter 9, but no GCR sites have been designated specifically for their representation. Thus a brief review of the suites is presented below.

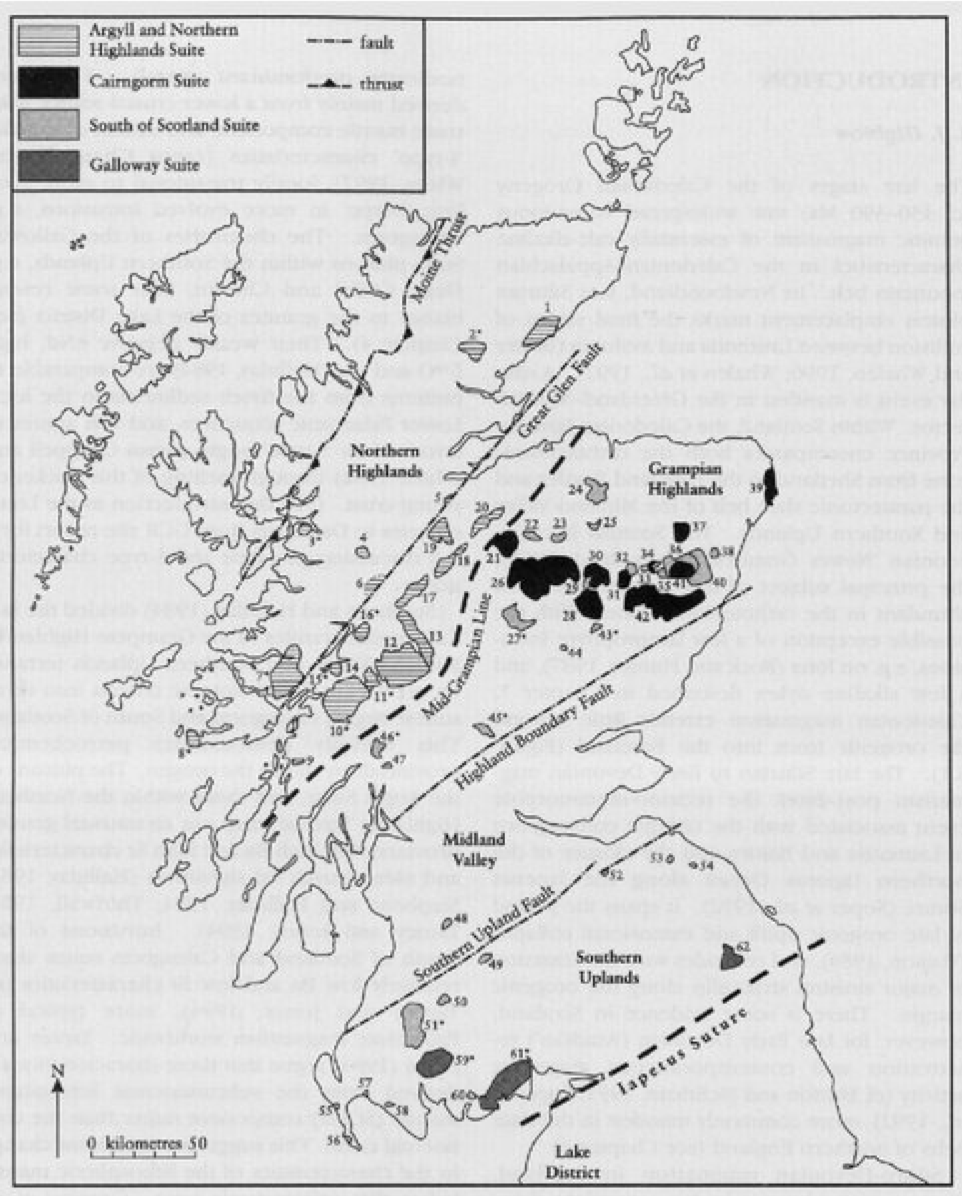
In general the background magmatism throughout the province is lamprophyric, with both hornblende- and mica-phyric types of calc-alkaline lamprophyre present (spessartite, vogesite, kersantite and minette). Overall, mica lamprophyres such as the minettes are more abundant in the Northern Highlands, while in the Southern Uplands spessartites are more common. The more primitive lamprophyric magmas generally provide a window into the nature and melt characteristics of the subcontinental lithospheric-mantle source area (Canning *et al.,* 1996; Fowler and Henney, 1996).

Deformed and/or metamorphosed intrusions are common to both the ortho- and paratectonic zones (Dearnley, 1967; Winchester, 1976; Smith, 1979; Barnes *et al.,* 1986; May and Highton, 1997). In the Highland terranes, these mainly sheet intrusions post-date the *c.* 470 Ma Caledonian tectonothermal peak and the *c.* 450 Ma late orogenic granite-pegmatite complexes, e.g. Glenmoriston, Arkaig, Kyllachy and Strathspey. Most pre-date emplacement of the *c.* 425–415 Ma, mid-crustal plutons of the Argyll and Northern Highlands Suite (cf. Smith, 1979). Later sheared intrusions, (syn- to post- 420 Ma plutons) are prevalent throughout the orthotectonic zone. Shear fabrics in some intrusions result from deformation penecontemporaneous with pluton emplacement (cf. Hutton and McErlean, 1991). This is illustrated in the Glen More River section of the Glen More GCR site, where shearing in some intrusions is a function of regional strike-slip movement. South-east of the Highland Boundary Fault, early lamprophyre dykes post-date the main deformation of the Palaeozoic succession but pre-date pluton emplacement. Folding and shearing of these intrusions occurred during compressional deformation towards the end of terrane accretion (Barnes *et* ed., 1986).

North-east- or ENE-trending dyke-swarms are particularly prominent within the upper crustal/subvolcanic environment. Some, for example the Ben Nevis, Etive, Distinkhorn and Doon swarms, are closely associated with plutons. The Cruachan Reservoir and Bonawe to Cadderlie Burn GCR sites, described in this chapter, and the Buchaile Etive Beag and Ben Nevis and Allt a Mhuillin GCR sites of Chapter 9, demonstrate the linkage between dyke-swarms and the multipulse Etive and Ben Nevis plutons, respectively. Swarms are less prominent adjacent to deeper-level plutons, but examples include the swarm of kersantites and spessartites that cut the Ross of Mull pluton locally, as seen in the Knockvologan to Eilean a' Chalmain and Cnoc Mor to Rubh' Ardalanish GCR sites (Rock and Hunter, 1987). A small composite swarm of spessartite to quartz-micromonzonite intrusions accompanies the Ratagain pluton (Glen More GCR site) (May *et al.*, 1993). Other small swarms associated with the Comrie pluton (Craig More and Funtullich GCR sites), Garabal Hill–Glen Fyne igneous complex (Garabal Hill to Lochan Dubh-Uisge GCR site) and Arrochar plutons, mostly comprise microdiorite and spessartite. To the south of the Highland Boundary Fault, widespread but not abundant minor intrusions within the Midland Valley are mostly microdiorites with some kersantites and minor acid variants (Swarbrick, 1992). Intrusions mostly take the form of dykes, although large sills and bosses occur in the Ochil and Sidlaw hills. Here, dyke-swarms are closely associated with the volcanic sequences, a feature reflected in their chemistries.

Lamprophyric intrusions are a significant component of the late Caledonian magmatism in the Southern Uplands (Rock *et al.,* 1986b; Henney, 1991; Shand *et al.,* 1994). Although a significant number of swarms are centred on the granitic plutons such as Loch Doon (Loch Dee GCR site), regional swarms are widespread. Most comprise hornblende-bearing lamprophyres and porphyritic microgranodiorites. A major ENE-trending swarm of largely mica-rich lamprophyres (mostly kersantites and minor minettes), with spessartites, microdiorites and a minor balsaltic component, extends from St Abb's through Dumfries-shire, the Mull of Galloway and into Northern Ireland (Read, 1926; Reynolds, 1931; Macdonald *et al.,* 1986; Rock *et W.,* 1986b). Near Kircudbright, the majority of the lamprophyre intrusions are contemporaneous with vents (see the Shoulder 0' Craig GCR site report, Chapter 9) and the sub-volcanic Black Stockarton Moor complex (Rock *et al.,* 1986a; Rock *et al.,* 1986b), and they predate the Criffel pluton.

References



(Figure 8.1) Late Caledonian granitic intrusions and plutonic suites of Scotland (starred numbers indicate those intrusions with GCR sites, named it italic type below): 1, Helmsdale; 2, Rogart (Loch Airighe Bheg); 3, Ratagain (Glen More); 4, Cluanie; 5, Abriachan; 6, Glen Garry; 7, Strontian (Loch Sunart); 8, Ross of Mull (Cnoc Mor to Rubh' Ardalanish and Knockvologan to Eilean a'Chlamain); 9, Kilmelford; 10, Etive (Bonawe to Cadderlie Burn and Cruachan Reservoir); 11, Glencoe fault intrusion (Stob Mhic Mhartuin and Loch Achtriochtan, Chapter 9); 12, Rannoch Moor; 13, Strath Ossian; 14, Ballachullish; 15, Duror of Appin (Ardsheal Hill and Peninsula and Kentallen); 16, Ben Nevis (Ben Nevis and Allt a'Mhuilinn, Chapter 9); 17, Corrieyairack; 18, Allt Crom; 19, Foyers; 20, Findhorn; 21, Monadhliath; 22, Boat of Garten; 23, Dorback; 24, Ben Rinnes; 25, Glen Livet; 26, Cairngorm; 27, Glen Tilt (Forest Lodge); 28, Lochnagar; 29, Craig Nardie; 30, Glen Gairn/Coilacreach; 31, Ballater; 32, Logie Coldstone; 33, Tomnaverie; 34, Cromar; 35, Torphins; 36, Balblair; 37, Bennachie; 38, Clinterty; 39, Peterhead; 40, Crathes/Gask; 41, Hill of Fare; 42, Mount Battock; 43, Glen Doll (Red Craig); 44, Glen Shee; 45, Comrie (Funtullich and Craig More); 46, Garabal Hill (Garabal Hill to Lochan Strath

Dubh-uisge); 47, Arrochar; 48, Distinkhorn; 49, Spango; 50, Cairnsmore of Carsphairn; 51, Loch Doon (Loch Dee); 52, Broad Law; 53, Priestlaw; 54, Cockbums Law; 55, Cairngarroch Bay; 56, Portencorkrie; 57, Glenluce; 58, Mochrum Fell; 59, Fleet (Clatteringshaws Dam Quarry and Lea Larks); 60, Black Stockarton Moor; 61, Criffel (Lotus Quarries to Drungans Burn and Millour and Airdrie Hill); 62, Cheviot.