Caledonian Igneous Rocks of Great Britain

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Chapter 8

Late Silurian and Devonian granitic intrusions of Scotland

INTRODUCTION

A. J. Highton

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') re-activation 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 ϵNd, high δ^{18}O and ϵSr (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 lithospheric 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

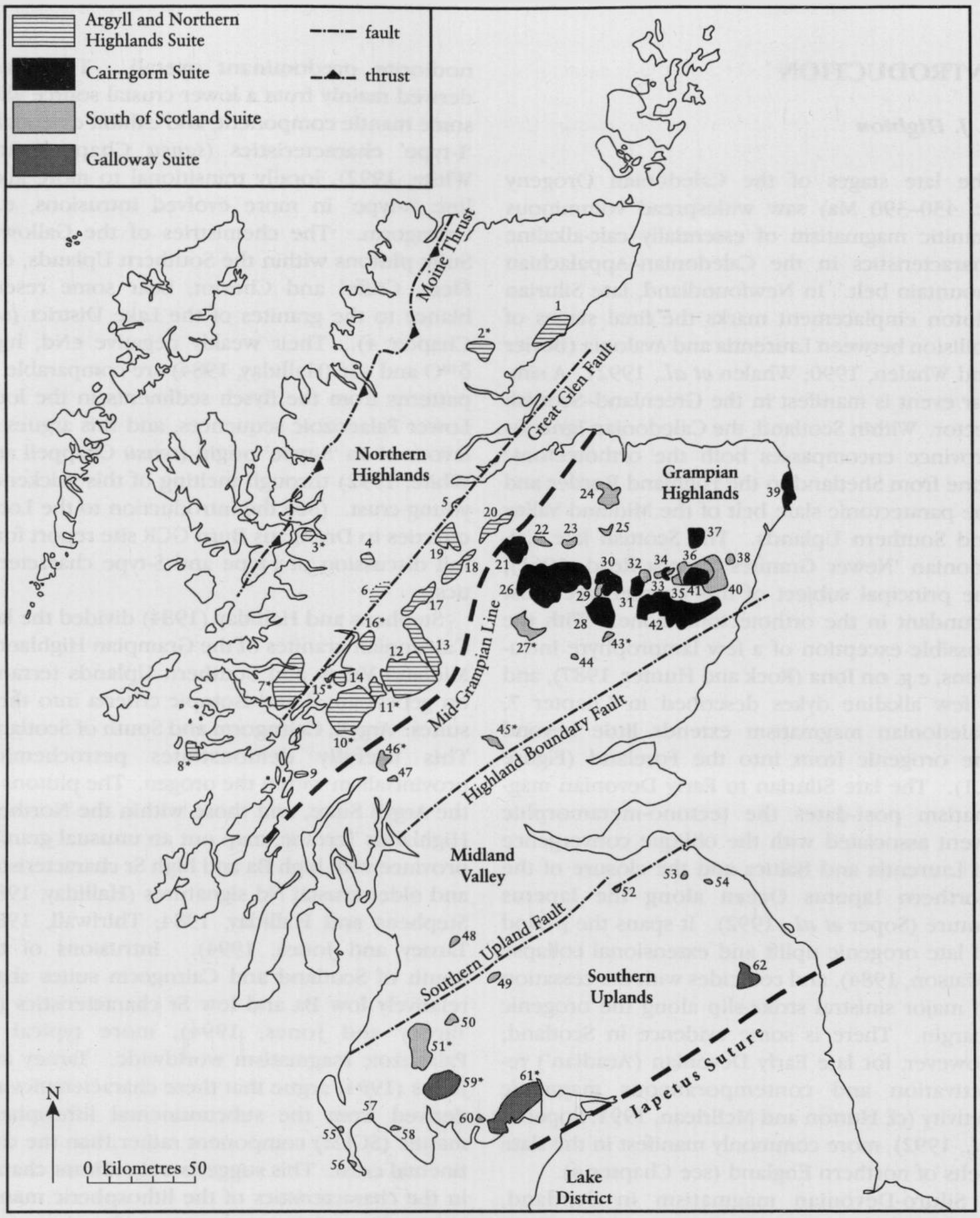


Figure 8.1 Late Caledonian granitic intrusions and plutonic suites of Scotland (starred numbers indicate those intrusions with GCR sites, named it italic type below):
1, Helmsdale; 2, Rogart (*Loch Airighe Bheg*); 3, Ratagain (*Glen More*); 4, Cluanie; 5, Abriachan; 6, Glen Garry; 7, Strontian (*Loch 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, Cockburns 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.

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 transcurrent 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 monzogranitic components. The plutons are strongly metaluminous ($CaO + Na_2O + K_2O > Al_2O_3 > Na_2O + K_2O$) with high Na, Sr and Ba and low Th, Nb and Rb. All have characteristically very low ϵNd values, -10 to +3, generally high ϵSr, -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 calc-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 phases 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 facies 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 facies 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 synplutonic 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 microgranite 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' ($^{87}Sr/^{86}Sr \sim 0.706$), highly evolved, and quite distinct from the other suites, with low Ti, P, Ba, Sr and K/Rb, and high Rb, Nb, Th and U. The isotopic signatures bear some similarity to the Argyll Suite, having low ϵNd values, –8 to –1, generally high ϵSr, +24 to +33 and $\delta^{18}O$ 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 Neoproterozoic 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 ($CaO + Na_2O + K_2O > Al_2O_3 > Na_2O + K_2O$) 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 ϵNd values, -6 to -1, generally high ϵSr, +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 al.*, 1997).

All of the plutons include members with S-type peraluminous characteristics ($Al_2O_3 > CaO + Na_2O + K_2O$) 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‰, while ϵNd 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 metaluminous 'I-type' outer facies to a core with peraluminous '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 co-workers, 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 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 monzonite), 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 al.*, 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 al.*, 1986b). Near Kircudbright, the majority of the lamprophyre intrusions are contemporaneous with vents (see the Shoulder O' Craig GCR site report, Chapter 9) and the subvolcanic Black Stockarton Moor complex (Rock *et al.*, 1986a; Rock *et al.*, 1986b), and they predate the Criffel pluton.

LOCH AIRIGHE BHEG (NC 703 025)

N. J. Soper

Introduction

The Rogart igneous complex extends over about 115 km² in SE Sutherland (Figure 8.2). It has been described by Read *et al.* (1925, 1926) and Soper (1963), and consists of a zoned quartz-monzodiorite–granodiorite–granite pluton, together with a peripheral zone of migmatization. The complex was emplaced into metasedimentary rocks of the Altnaharra Formation in the Morar Group of the Moine Supergroup after the main, presumed Caledonian, deformation. It is overlain by Devonian strata of Old Red Sandstone facies. It therefore belongs to the late Caledonian 'Newer Granites' and is a component of the Argyll and Northern Highlands Suite.

The scale of the migmatitic envelope of the Rogart complex is unique in British Caledonian granites, and three GCR sites have been chosen to illustrate its features, Creag na Croiche, Aberscross Burn–Kinnauld and Brora Gorge. These are to be described in the *Lewisian, Torridonian and Moine Rocks of Scotland* GCR volume. The Loch Airighe Bheg GCR site described here displays features of the intrusive part of the complex, the pluton, together with hybridized appinitic rocks that occur as xenoliths.

The Appinite Suite of alkalic ultramafic, intermediate and felsic intrusive rocks is intimately associated with late Caledonian plutons throughout the Scottish Highlands. The type area of the suite is described in this GCR volume (see the Ardsheal Hill and Peninsula GCR site report). Appinitic intrusions are widely developed in the Moine rocks of the Northern Highlands where they form isolated bosses, often a hundred metres or so across. They were described by Read *et al.* (1925) as 'hybrids of Ach'uaine type', from a locality some 10 km SW of this GCR site (NH 624 952), where they range in composition from ultramafic olivine-pyroxene-amphibole-biotite rocks to granodiorite. Read interpreted the diversity of the suite as a result of hybridization of granitic magma with either ultrabasic magma or solid rock. More recent geochemical studies have invoked the contamination of mantle-derived, K-rich (shoshonitic) basic magmas (Fowler, 1988a; Fowler and Henney, 1996).

Description

The GCR site is located near the south-eastern margin of the Rogart pluton (Figure 8.2). This intrusion consists of hornblende-biotite granodiorite that grades into a marginal quartz-monzodiorite and is cut by a body of granite; the quartz-monzodiorite and granite are exposed at the site, but not the granodiorite.

The quartz-monzodiorite crops out immediately east of the loch and at Dalmore Quarry 600 m to the NE (709 029). At the latter locality it is composed of plagioclase An_{23} (50%), quartz (18%), K-feldspar (12%), biotite (10%) and amphibole (8%), together with minor titanite, allanite, zircon and apatite. It is cut by aplitic microgranite, granite pegmatite and rare microgranodiorite veins (Figure 8.3). The quartz-monzodiorite has a foliation defined by the preferred orientation of biotite, amphibole and to some extent plagioclase. This foliation is subvertical and here strikes NE, roughly parallel to the contact of the outer facies with its migmatitic envelope. Surfaces parallel to the foliation show a weak linear fabric, defined mainly by the alignment of amphibole, which plunges gently north-

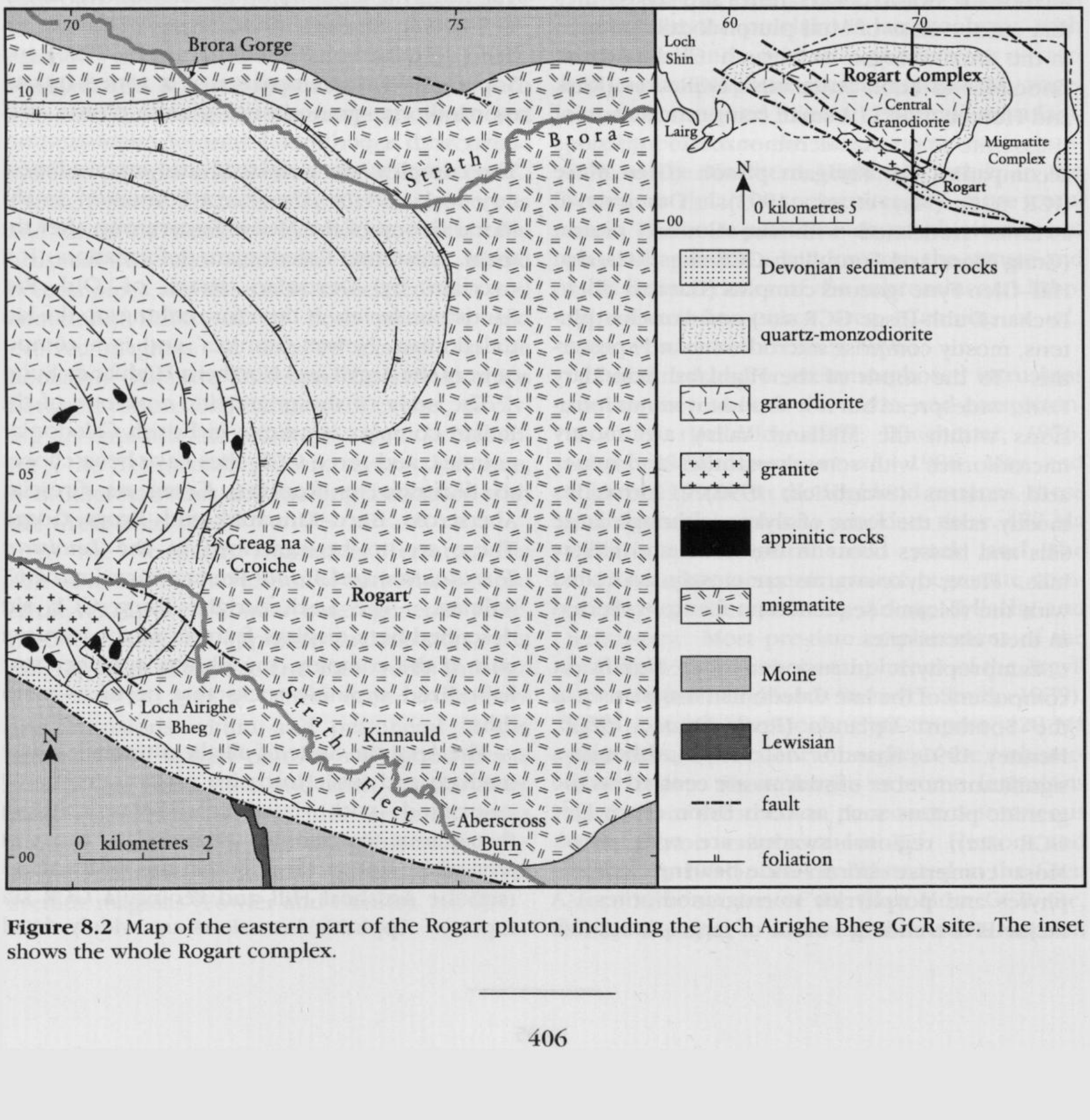


Figure 8.2 Map of the eastern part of the Rogart pluton, including the Loch Airighe Bheg GCR site. The inset shows the whole Rogart complex.

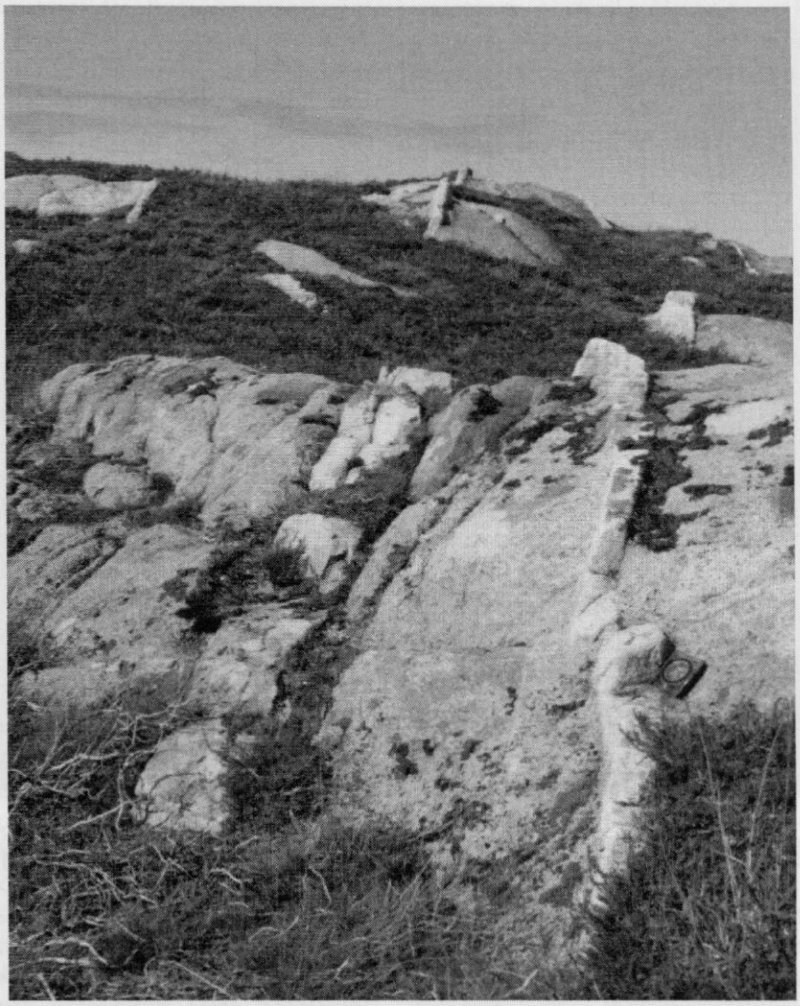


Figure 8.3 Poorly foliated outer quartz-monzodiorite of the Rogart pluton cut by veins of aplitic microgranite (NC 704 025). (Photo: Susan Hall.)

eastwards.

The later granite, exposed in the northern part of the GCR site, consists essentially of plagioclase An_{12} (50%), quartz (26%), K-feldspar (18%) and biotite (6%). It is unfoliated and although its contact with the quartz-monzodiorite is not exposed here, elsewhere there is a narrow gradation between the facies.

Crags immediately to the north and NW of the loch are composed of a wide variety of appinitic lithologies, ranging from ultramafic types composed of pyroxene, amphibole, biotite and minor feldspar to meladiorite and melanocratic syenogranite; the commonest type is made of amphibole and biotite with patches of pink K-feldspar. Angular to sub-rounded appinitic xenoliths are enclosed by the host quartz-monzodiorite, with biotite-rich selvages developed locally at the contact (Figure 8.4). Larger appinitic masses are veined by hornblende-rich quartz-monzodiorite and contain patches of hornblende-K-feldspar pegmatite.

Interpretation

In a structural study of the Rogart complex, Soper (1963) interpreted the foliation and sub-horizontal linear fabric in the outer quartz-monzodiorite as the result of ballooning during its final emplacement. Evidence that the pluton deformed and eventually punched through its own migmatite envelope is illustrated by the sites in the *Lewisian, Torridonian and Moine Rocks of Scotland* GCR volume.

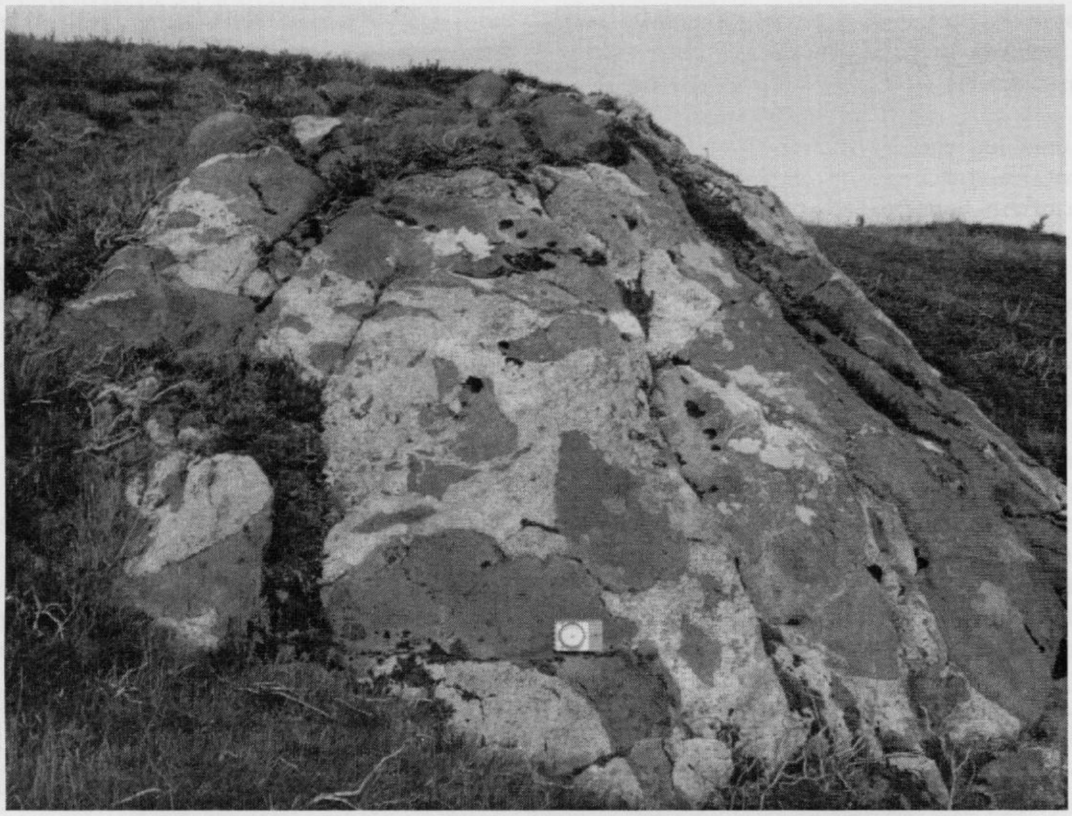


Figure 8.4 Xenoliths of appinitic rock in quartz-monzodiorite of the Rogart pluton (NC 703 026). Dark biotite-rich selvages are visible at the margin of the xenolith above the compass. (Photo: Susan Hall.)

Read (1961) classified the 'Newer Granites' into 'forceful' and 'permitted'. The 'forceful' intrusions were emplaced by shouldering aside the country rocks and were thought to be deeper and older than the 'permitted' high-level, subvolcanic granites emplaced by brittle mechanisms: the Rogart pluton was cited as an example of the forceful type. While modern views on pluton emplacement emphasize tectonic controls on space creation (Hutton, 1988a), in the Highlands it is evident that concordant, foliated intrusions such as Rogart were emplaced in a more ductile environment than nearby cross-cutting plutons such as Helmsdale (Figure 8.1). The K-Ar age of the Rogart complex is about 420 Ma (Brown *et al.*, 1968), similar to K-Ar ages generally obtained from the Moine rocks of the Northern Highlands, suggesting that the complex was emplaced during the waning stages of regional metamorphism and cooled together with the country rocks during late orogenic uplift and erosion. The K-Ar age of the Helmsdale pluton is about 400 Ma (Brown *et al.*, 1968), and so this intrusion is likely to have been emplaced after substantial erosion had taken place. Thus Read's view that the 'forceful' Highland granites were deeper and older than the 'permitted' types is essentially true.

The 'Ach'uaine hybrids' are regarded as a component of the late Caledonian 'Newer Granite' magmatism (Read *et al.*, 1925). Fowler (1988a) interpreted them as differentiates of relatively primitive, K-rich mantle-derived magma that crystallized under hydrous conditions with some crustal contamination. Fowler and Henney (1996), however, invoked the mixing of shoshonitic magma with contemporaneous syenitic magma. The appinitic masses at Loch na Airighe Bheg are xenoliths within the quartz-monzodiorite, not intrusions, so their emplacement pre-dates that of the Rogart pluton at the level now exposed. No modern petrogenetic investigation of these rocks has been undertaken, so it is uncertain to what extent their compositional diversity is a result of hybridization with the Rogart magma.

Conclusions

The Rogart complex is a member of the Argyll and Northern Highlands Suite of late Caledonian intrusions, emplaced into metasedimentary rocks of the Moine Supergroup. It consists of a quartz-monzodiorite–granodiorite–granite pluton flanked to the east and north by a concordant aureole and migmatite envelope. At the Loch Airighe Bheg GCR site several components of the pluton are exposed. The quartz-monzodiorite is foliated roughly parallel to its nearby contact with the migmatized envelope and also carries a weak sub-horizontal alignment of amphibole. This is thought to be due to ballooning of the quartz-monzodiorite–granodiorite magma during its emplacement. The later inner granite is unfoliated and apparently discordant.

The most interesting feature of the site is the presence of numerous appinitic xenoliths within the quartz-monzodiorite. These belong to a regional suite of mantle-derived, K-rich mafic intrusions known as the Ach'uaine hybrids. The xenoliths show a wide range of structural, textural and mineralogical relationships with the surrounding quartz-monzodiorite, which would repay further investigation to establish to what extent the compositional diversity of the appinitic rocks at this locality is a result of hybridization with the host quartz-monzodiorite.

GLEN MORE (NG 861 201–917 188)

W. E. Stephens

Introduction

The Ratagain pluton is distinctive among the late Caledonian intrusions of Scotland in having compositional features transitional between the alkaline intrusions of Assynt and the NW Foreland (see Chapter 7) and the more common metaluminous calc-alkaline intrusions of the Argyll and Northern Highlands Suite. In this sense it forms a link between these very different but near-contemporaneous periods of magmatism. The pluton shows considerable petrological variety in a small area (*c.* 17 km^2), and also has some notable compositional characteristics, having among the highest known Sr and Ba abundances for such rock types anywhere. The presence of mafic (meladiorite) bodies and a degree of mingling between mafic masses and felsic magmas are well displayed, in common with several other plutons lying between the Great Glen Fault and the Moine Thrust. It is one of the few plutons in Scotland that hosts gold-bearing veins.

The pluton was first described by the Geological Survey (Peach *et al.*, 1910), and a detailed petrological account was presented by Nicholls (1951a, b). An extension to the intrusion was recognized by Dhonau (1964), and the main pluton was characterized geochemically and isotopically by Halliday *et al.* (1984) and Hutton *et al.* (1993). A new map of the pluton, taking advantage of many new exposures associated with local forestry activities, has revised the various petrological facies and their distribution (Hutton *et al.*, 1993). Emplacement of the pluton in relation to movements on regional faults systems was the subject of a further study by Hutton and McErlean (1991).

The pluton was emplaced at 425 ± 3 Ma (U-Pb baddelyite age from the pyroxene-mica diorite facies; Rogers and Dunning, 1991). A Rb-Sr mineral-whole rock isochron age of 415 ± 5 Ma (Turnell, 1985) is now regarded as too young and is taken to reflect the fairly rapid cooling history of the complex. These data indicate that the pluton was emplaced more-or-less contemporaneously with late members of the Assynt alkaline suite such as the Ben Loyal syenite (van Breemen *et al.*, 1979a; Halliday *et al.*, 1987).

In recent years this pluton has contributed to the debate over the role of subduction in the origin of the Caledonian granites, the compositions of some components having been correlated with those of shoshonitic lavas, which tend to be associated with the deepest parts of subduction zones (Thompson and Fowler, 1986).

The Glen More GCR site contains all the important members of the pluton, as well as, at Braeside, the only outcrops of an olivine-gabbro component. The site includes the hillside of Moyle Wood in which various relationships between earlier and later members of the pluton are well displayed. Good examples of the small mafic bodies previously described as 'appinites' are well exposed in the Glen More river.

Description

The Ratagain pluton comprises principally diorites and quartz-monzonites (Figure 8.5). The

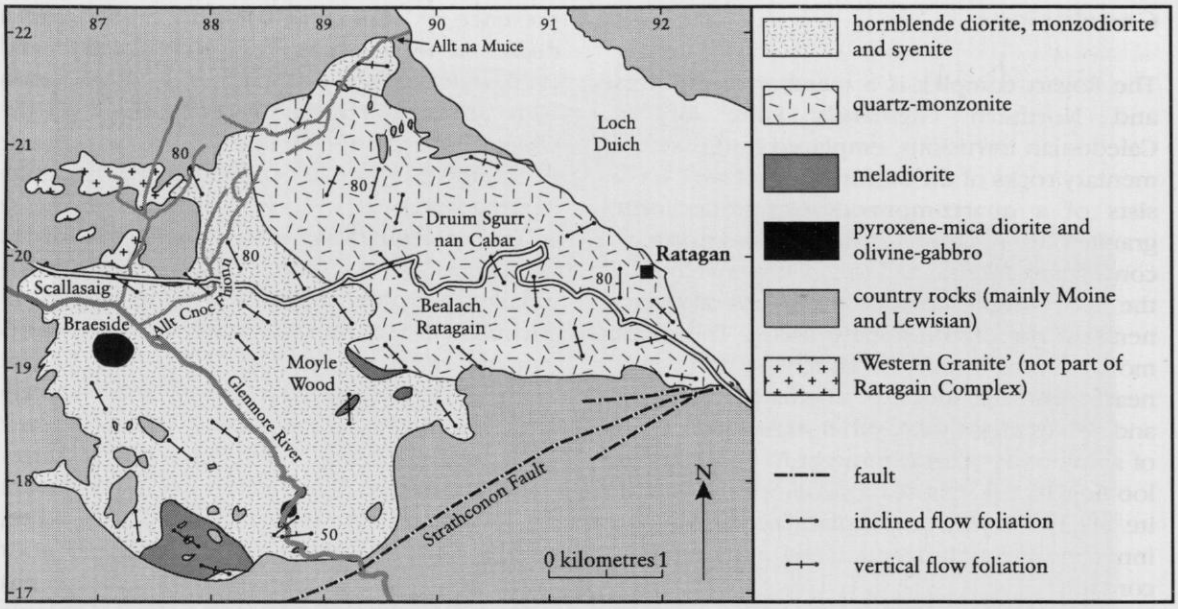


Figure 8.5 Map of the Ratagain pluton, adapted from Hutton *et al.* (1993).

diorites tend to occupy the low ground around Glen More and the valley sides of Moyle Wood. These are cut by later quartz-monzonites which form the hill of Druim Sgurr nan Cabar, above the Bealach Ratagain, and its easterly slopes down to Loch Duich. Overall, the pluton has shallow-dipping walls, where they can be mapped, but the main internal contact between the diorite and the quartz-monzonite is rather steep. In the Glen More region, the present topographical surface appears to be nearly parallel to the roof of the diorite.

The main diorite mass is highly xenolithic with abundant mafic-rich enclaves and some metasedimentary inclusions, all of which are well exposed in the Glen More river and in some tributaries such as the Allt Cnoc Fhionn. The diorites are usually medium grained with hornblende, biotite and plagioclase as the principal minerals, with accessory titanite and minor celestine. Compared with other diorites in the late Caledonian suites, these display considerable textural and mineralogical heterogeneity. One poor exposure of considerable petrogenetic importance in southern Glen More at Braeside is of pyroxene-mica diorite associated with olivine-gabbro (Figure 8.5).

Included within the diorite are large rafts of metasedimentary rock as well as mafic bodies originally described as 'appinites' (Figure 8.6). However these 'appinites' contrast strongly with the type appinites of Appin in Argyll in which amphibole is generally idiomorphic (see the Ardsheal Hill and Peninsula GCR site report). Amphibole is only rarely idiomorphic in the Ratagain rocks and biotite is more abundant than in the type appinites; hence the term meladiorite is preferred. These rocks are best displayed in forestry road cuttings in Glen More and in the woods to the NE. Some of the meladiorite masses may have been intruded in a solid state as pipe-like bodies facilitated by felsic magma. This is suggested by an exposure in a small quarry within Moyle Wood, where pillow-like meladiorite masses are vertically aligned within a monzonitic matrix. While most of these meladiorite bodies have igneous textures at least one example in the Glen More river is banded with layers containing abundant titanite poikilitically enclosed within large alkali feldspars. Petrographical and geochemical evidence indicates that some of these mafic masses may be the result of interaction between diorite and local calcareous metasedimentary rocks, as originally suggested by Nicholls (1951a).

The pink- or buff-coloured quartz-monzonites were intruded late (Figure 8.5), and it is difficult to find sharp contacts with the earlier diorites, most being transitional over about 200 m. An approximate boundary zone can be traced in the

Figure 8.6 Net-veined meladiorite ('appinite') from the Ratagain pluton. (Photo: W.E. Stephens.)

cuttings of the Glenelg–Ratagain road and in the forestry tracks in the northern parts of Moyle Wood. Away from the contact, veins of felsic monzonites intrude brittle fractures in the diorites. The quartz-monzonite adjacent to the contact is rich in mafic minerals, bearing conspicuous hornblende-rich aggregates, and containing large meladiorite inclusions (up to 0.5 m) in places. Farther into the quartz-monzonites, i.e. towards the interior of the pluton, the abundance of quartz appears to increase, although this has not been quantified.

As discussed later, much has been made of the syenitic rocks within the Ratagain pluton (e.g. Thompson and Fowler, 1986). The petrological map of Nicholls (1951a) shows extensive outcrops of syenite in the Glen More and Moyle Wood areas of this GCR site. Exposures of syenitic rocks can indeed be found, for instance at the junction of the Allt Cnoc Fhionn and the main road, but all are small (metres scale) and enclosed within the more evolved diorites. Thus the syenite is regarded as a local facies rather than as a major member of this pluton (Hutton *et al.*, 1993). Nicholls' petrological map also indicates outcrops of 'Western Granite' to the NE of the Glen More river at Scallasaig, which were interpreted as the earliest member of the pluton (Nicholls, 1951a). Mapping by Hutton *et al.* (1993) and associated geochemical studies have shown that this granite is not part of the main Ratagain pluton.

Interpretation

Strongly alkaline granites (*sensu lato*) are unusual and are normally associated with extensional tectonic environments, yet the contemporaneous alkaline syenitic rocks of Assynt (some 100 km to the north of Ratagain) are clearly associated with regional movements on the Moine Thrust, so precluding an extensional origin (see Chapter 7). Thompson and Fowler (1986) highlighted the similarity of the Ratagain syenites with those of Glen Dessarry, Loch Borralan and Loch Ailsh and argued that they were derived from deep asthenospheric mantle sources in a subduction-related setting. However, most recent studies have shown the syenites to be a relatively insignificant facies of the Ratagain pluton and hence they cannot be representative of the mass as a whole (Hutton *et al.*, 1993). An isotopic study of the whole pluton by Halliday *et al.* (1984) established that both mantle and crustal sources were involved in the genesis of the magmas, but detected no subduction-related characteristics.

Compositionally the whole pluton has some most unusual features for a late Caledonian granitic intrusion. As well as unusually high levels of alkalis, especially Na_2O, the trace elements Sr (1000–5000 ppm), Ba (1000–6000 ppm), and Ce (representing the light rare earth elements, 70–400 ppm) are extremely high. These enrichments are not closely correlated, with higher Sr tending to be found in the diorites and Ba being enriched in the monzonites. The origin of this extreme enrichment in incompatible trace elements is still not resolved (Hutton *et al.*, 1993). Such trace element characteristics in intermediate magmas are uncommon in typical subduction regimes, but are known from post-subduction and ridge-subduction systems (Saunders *et al.*, 1987).

The variety of igneous rocks in the pluton is greatest in the Glen More area, virtually spanning the whole range. Olivine-gabbros and pyroxene-mica diorites near the outer contact at Braeside have quenched magmatic textures and thus provide evidence of potential parental basic magmas to at least some facies within the pluton (Hutton *et al.*, 1993). The more basic rock types at Ratagain, including the pyroxene-mica diorite and meladiorite have unambiguous mantle isotopic signatures, which vary sufficiently to suggest that the mantle sources were heterogeneous. The more evolved rock types, including the quartz-monzonites and some diorites, have isotopic signatures that indicate interaction with crustal sources, though not the local metasedimentary rocks (Halliday *et al.*, 1984). The syenitic rocks, which Thompson and Fowler (1986) regarded as K-rich shoshonites with a mantle origin, are in fact more sodic than potassic and are probably local variants of the diorites.

Nicholls (1951a) explained the variety of rocks in the pluton in terms of the co-existence of a calc-alkaline magma of 'Newer Granite' affinity and an alkaline magma of Assynt and Ben Loyal affinity, which underwent extensive hybridization, both at depth and after emplacement. Field evidence in Moyle Wood and in the road cuttings suggests that some hybridization has occurred between the diorites and the quartz-monzonites, and it is likely that the quartz-monzonites have also undergone some fractional crystallization.

A further unusual feature of this pluton in the context of the late Caledonian granitic suites is the rather oxidized condition of the magmas, with the presence of sulphates (celestine and baryte) in the igneous rocks. This condition in monzonites is known to favour the occurrence of gold (Cameron and Hattori, 1987), and indeed small amounts of gold mineralization have been described from late veins in the pluton (Alderton, 1986, 1988).

Conclusions

The Glen More GCR site contains all the major facies of the Ratagain pluton, as well as providing constraints on some of the important field relationships between these members. This single, rather small intrusion is important for its unusual transitional alkaline composition and its implications for the plate tectonic environment of the NW Highlands during late Caledonian times. It has been constructed from magmas derived from a wide range of mantle and crustal sources and could be important in providing a better understanding of the relationships between thrust tectonics and the tapping of magmas from their source regions. The pluton is most unusual, not just in the Caledonian rocks of Britain, but worldwide, in having extreme enrichments of the trace elements Sr and Ba. There is no close analogue anywhere in the world and further studies will contribute to an understanding of this rare type of geochemical enrichment.

LOCH SUNART (NM 776 607–872 593)

A. J. Highton

Introduction

The Strontian pluton (MacGregor and Kennedy, 1932; Sabine, 1963) occurs on the NW side of the Great Glen Fault and is assigned to the Argyll and Northern Highlands Suite of late

Caledonian granitic intrusions on the basis of its geochemical and isotopic characteristics (Halliday, 1984). The pluton falls into the category of 'forceful' intrusions, thought to have emplaced by diapirism (Read, 1961). As a means of pluton emplacement this mechanism is questionable, and alternative solutions have been presented (Hutton, 1988b). The Loch Sunart GCR site presents a cross section through the northern part of the Strontian pluton. Significant features include evidence for intrusion of basic magma contemporaneous with pluton emplacement, and fabrics resulting from syn-emplacement deformation.

The pluton extends over an area of some 200 km² in a N–S-trending outcrop from the NW shores of Loch Linnhe to the southern slopes of Meall a' Ghruith (822 653). It comprises:

1. an outer hornblende-biotite granodiorite facies, with porphyritic and non-porphyritic variants ('tonalite' and 'granodiorite' of early workers)
2. an inner biotite granodiorite ('biotite granite' or 'adamellite' of early workers) that extends eastwards as a vein complex cross-cutting the metasedimentary envelope (Figure 8.7).

These are referred to respectively as the Loch Sunart granodiorite and Glen Sanda granodiorite facies (Paterson *et al.*, 1992a, b). Mafic enclaves, including some large bodies of appinitic meladiorite, are common in both facies (Holden, 1987). Although previously dated at 435 ± 10 Ma (Pidgeon and Aftalion, 1978), recent zircon studies give an emplacement age of 425 ± 3 Ma for the hornblende-biotite granodiorite (Rogers and Dunning, 1991) and 418 ± 1 Ma for the biotite granodiorite facies (Paterson *et al.*, 1993). The latter facies, however, has a significant inherited zircon component (Paterson *et al.*, 1992a, b).

The envelope consists of middle to upper amphibolite facies metasedimentary rocks of the Glenfinnan and Loch Eil groups of the Moine Supergroup. A 3 km-wide high-grade, sillimanite-bearing thermal aureole encloses the pluton, from which Tyler and Ashworth (1982) derived a pressure estimate of 4 kbar. Along its northern contact, the pluton truncates the outcrop of the Precambrian West Highland Granite Gneiss (Barr *et al.*, 1985; Friend *et al.*, 1997), while the Great Glen Fault terminates the south-eastern boundary of the intrusion. Kennedy (1946) regarded

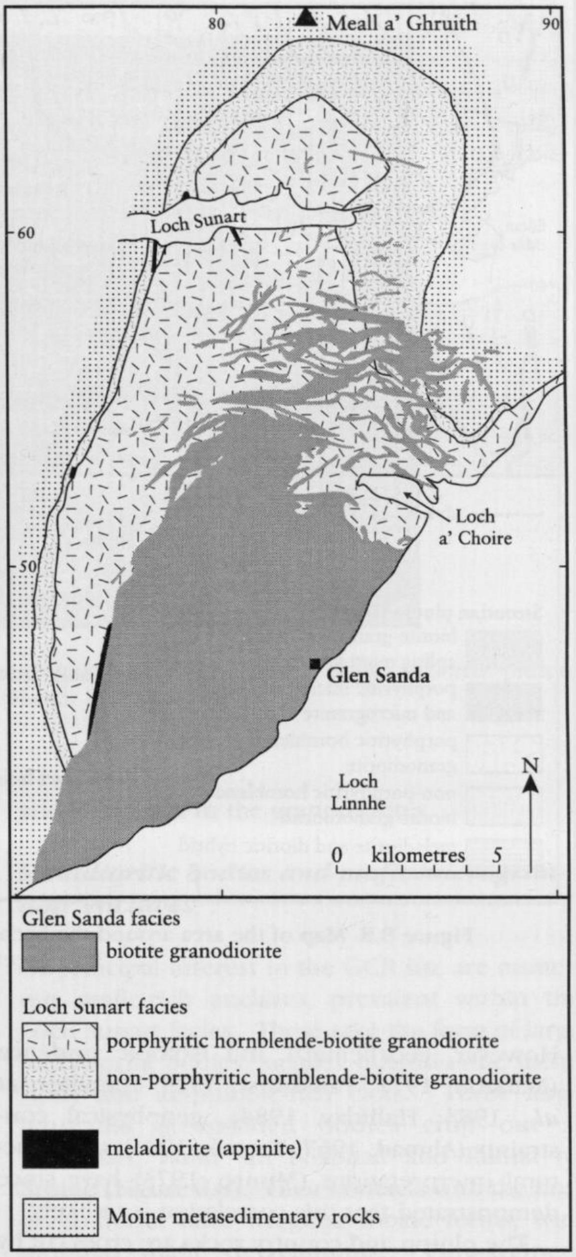


Figure 8.7 Map showing the distribution of facies within the Strontian pluton, adapted from Sabine (1963).

the Strontian outcrops and those at Foyers on the SE side of the fault as part of the same pluton, separated by a 105 km sinistral displacement. There are significant similarities in terms of lithologies, enclave populations, emplacement and synplutonic deformational histories, and both were intruded at corresponding crustal levels of *c.* 13 km (Tyler and Ashworth, 1983).

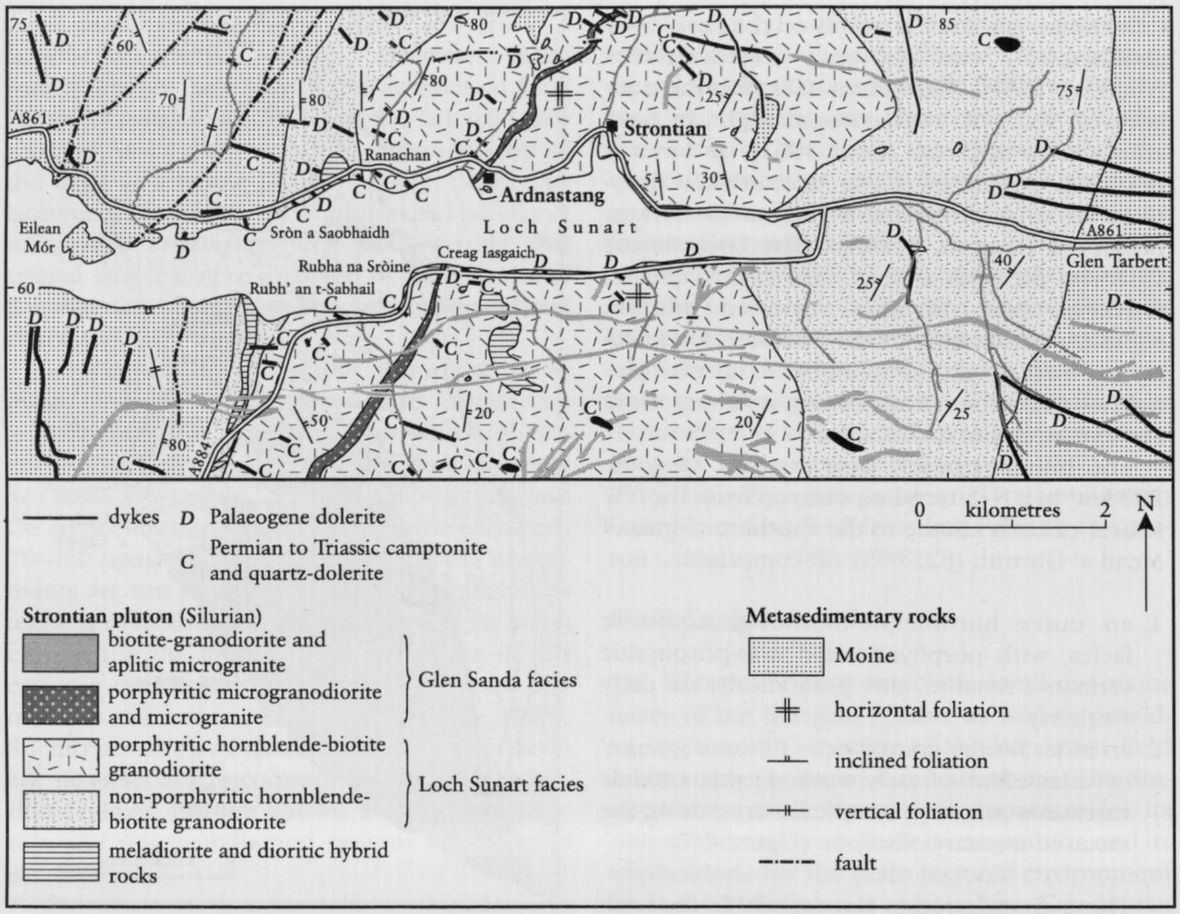


Figure 8.8 Map of the area around the Loch Sunart GCR site, Strontian pluton, adapted from BGS sheets 52E and 53.

However, geochemical and isotopic evidence (Marston, 1971; Pankhurst, 1979; Hamilton *et al.*, 1983; Halliday, 1984), geophysical constraints (Ahmad, 1967; Torsvik, 1984) and structural interpretations (Munro, 1973) have since demonstrated that this correlation is unlikely.

The pluton and country rocks are cross cut by Permian age ENE-trending camptonite dykes and quartz-dolerite plugs (Rock, 1983), and by later basic intrusions of Palaeogene age.

Description

The GCR site comprises a west to east traverse, including road cuttings, shoreline exposures along both sides of Loch Sunart, and the hills to the south of Glen Tarbert (Figure 8.8). It lies within the Loch Sunart facies of the Strontian pluton, which contains abundant mafic enclaves, and is cross-cut by veins of the Glen Sanda facies.

Margin and envelope

To the east of Sròn na Saobhaidh, the western contact of the pluton is steeply inclined against interlayered psammites and semipelites. Here, extensive recrystallization and a cordierite–K-feldspar assemblage represent the highest grade within the aureole. Sillimanite forms felts or less commonly coarse crystals, with cordierite, garnet and K-feldspar overgrowing the regional gneissose foliation. A migmatitic overprint, in the form of granitic segregation, disrupts the regional metamorphic fabrics within 500 m of the contact, but is absent from rocks west of Eilean Mór.

Loch Sunart facies

At the outer margin of the pluton, this hornblende-biotite granodiorite is a medium- to coarse-grained, strong to moderately foliated

Figure 8.9 Mafic microgranular enclaves (MME) in porphyritic biotite granodiorite of the Strontian pluton, Rubh' an Torr-mholaich, Loch Sunart (NM 8133 6015). (Photo: BGS no. C4000.)

non-porphyritic variant. Adjacent to the western contact aplitic microgranite veins and partially assimilated country rock xenoliths are numerous. The western contact between the outer non-porphyritic and inner porphyritic variant is transitional over a few metres, marked by the incoming of feldspar mesocrysts. On the south shore of Loch Sunart this boundary is partly obscured by a meladioritic intrusion, that is chilled against the non-porphyritic facies. The inner granodiorite is characterized by variably abundant pink microperthitic K-feldspar megacrysts (up to 2 cm long) and plagioclase phenocryts (up to 1 cm long). Both lithologies contain prominent phenocryst of pink-brown titanite up to 0.5 cm long.

A weak to strong foliation defined by the alignment of the ferromagnesian minerals and plagioclase, is present throughout most of the site. The foliation dips inwards, flattening towards the centre of the intrusion. It decreases in intensity away from the margins, and in the porphyritic facies, is often overgrown by the K-feldspar megacrysts. Abundant mafic-rich enclaves have regular ellipsoidal or lenticular shapes, flattened in the plane of the foliation. However, there is no evidence of any significant deformation or recrystallization of either the fabric-defining minerals or the interstitial quartz and K-feldspar in the granodiorites.

Meladioritic bodies and mafic microgranular enclaves

Of principal interest in the GCR site are numerous mafic-rich enclaves, prevalent within the Loch Sunart facies. These take the form of large meladiorite bodies, smaller microdioritic inclusions and amphibole-rich clots. Three large lenticular steep-sided bodies crop out at Ranachan, Rubh' an t-Sabhail and Rubha na Sròine (Figure 8.8). Their contacts with the host granodiorite have irregular lobate forms, with globular mafic detachments. Fine-grained, (?)chilled, margins are common, in which the ferromagnesian minerals have skeletal or crudely radial forms (7941 6016; 7852 6107). All show compositional zoning outwards from coarse-grained meladiorite to finer-grained heterogeneous, variably plagioclase-phyric, hybrid leucodiorites. The latter often enclose mafic-rich fragments. The hybrid marginal rocks are commonly either veined by the host granodiorite or net-veined by micrograntic pegmatite segregations. In hybrid rocks at the margin of the Rubh' an t-Sabhail body, the pervasive mineral fabric is refracted from the host granodiorite into the appinitic xenolith.

Mafic microgranular enclaves are abundant, forming trains of ellipsoidal fragments aligned parallel to the foliation fabric in the granodiorite host (Figure 8.9). The enclaves are predominantly hornblende-plagioclase quartz-diorites, and rarely porphyritic tonalites. The non-porphyritic granodiorite contains numerous amphibole-titanite-rich clots, up to 8 mm in diameter. Compositional zoning is common from marginal intergrowths of hornblende, biotite and plagioclase, enclosing largely monomineralic cores of actinolitic amphibole.

Minor intrusions of porphyritic microgranodiorite/granite

Rocks of the Loch Sunart facies and meladiorite bodies are cut by NE-trending sheets and/or dykes of compositionally heterogeneous porphyritic microgranodiorite and microgranite (Figure 8.8). A *c.* 20 m-wide intrusion crops out on both shores of Loch Sunart, to the west of Ardnastang and at Creag Iasgaich on the south shore. The intrusion contains both microdiorite and foliated mafic-rich microgranular enclaves, in varying stages of assimilation. Feldspar mesocrysts overgrow contacts between the hybrid rocks and enclaves.

Glen Sanda facies

This facies is not well represented within the GCR site (Figure 8.8), but sheets and dykes of a pink-grey, medium-grained biotite granodiorite extend northwards as far as Loch Sunart and Glen Tarbert. These sheets are mostly parallel sided, with sharp angular contacts; they contain xenoliths of hornblende-biotite granodiorite and lack the foliation that is ubiquitous in the earlier facies. They are variably feldspar-phyric, with pale-pink euhedral phenocrysts of plagioclase (up to 5 mm) enclosed by irregular white rims of albite and poikilitic mesocrysts of K-feldspar (up to 8 mm). Biotite is the predominant mafic mineral (with hornblende rare), but forms less than 10% of the rock.

Interpretation

The Strontian pluton contains two distinct facies, a hornblende-biotite granodiorite and a biotite granodiorite. A two-stage emplacement model has been suggested, with intrusion of the Loch Sunart followed by the Glen Sanda body (Munro, 1965, 1973). Sabine (1963) described the pluton as funnel shaped. Munro (1965) ascribed this form to initial intrusion of a stock-like mass centred in the southern part of the pluton. On reaching the level of emplacement, the magma body expanded laterally in a northerly direction, forcibly distending into the country rock envelope. The internal foliation in the Loch Sunart body was interpreted as a magmatic flow pattern, formed during forceful intrusion (MacGregor and Kennedy, 1932; Sabine, 1963; Munro, 1965). The Glen Sanda intrusion was seen as a later stock, with an apparently brittle mode of intrusion with stoping and sheeting, reflecting emplacement at a higher crustal level than the Loch Sunart intrusion (Munro, 1965). A considerable time gap was invoked to accommodate the apparent uplift, and current geochronology separates the intrusions by approximately 7 Ma. Given the estimated emplacement level of the Loch Sunart body at 14 km, an uplift rate in excess of 1 km per Ma would be necessary to accommodate the high level of intrusion implied for the Glen Sanda body.

More recent studies suggest that the internal foliation in the Loch Sunart facies is a pre-full crystallization fabric, rather than magmatic flow, with the highest strains occurring towards the margins of the pluton (Hutton, 1988a, b). Minerals both defining the fabric and filling the interstices show little evidence of recrystallization. Hence, the foliation in the northern part of the pluton is not a high temperature solid-state tectonic fabric, but reflects the impositon of strain upon an inward accreting crystal framework. Crystal plastic strain fabrics are present in the hornblende-biotite granodiorite elsewhere in the pluton, adjacent to the western boundary with the biotite granodiorite intrusion (Hutton, 1988b). This is an indication of continuing imposition of strain after local consolidation. The variation in orientation of the foliation within the northern part of the pluton (well illustrated within the GCR site), coupled with asymetric vein shear-sense indicators (seen elsewhere), was interpreted by Hutton (1988b) as consistent with a southerly directed listric extension at the time of emplacement, rather than with diapirism or ballooning. Space created during this deformation, at the extensional termination of a dextral shear splay of the Great Glen Fault, allowed the intrusion of the later biotite granodiorite (Hutton, 1988a, b).

Mafic-rich enclaves are common inclusions within 'I-type' granitic intrusions, and are abundant within the Strontian pluton. They have been interpreted as disrupted precursor 'appinite' and microdiorite intrusions (MacGregor and Kennedy, 1932; Sabine, 1963). However, recent studies suggest that the enclaves represent synplutonic basaltic intrusions and autoliths, which have mantle isotopic signatures (Holden, 1987; Holden *et al.*, 1987; Holden *et al.*, 1991; Stephens *et al.*, 1991). Interaction of these hydrous basic melts with the host granitic magma has given rise to the dioritic hybrids (Holden *et al.*, 1987). The lobate margins to most of the enclaves are indicative of liquid–liquid contacts, with the fine-grained edges representing quenching against a lower temperature host granitic magma. The liquid–chill contacts with differing granitic facies implies episodic intrusion of basic magma throughout pluton emplacement.

Castro and Stephens (1992) suggested that the amphibole-rich clots formed as reaction products between pyroxene and the host magma. The source of the pyroxene is equivocal. They may either represent phenocrysts from the basic magma dispersed during mingling with granodioritic magma, or they may have been derived from the source as restite. The granoblastic textures within the clots might favour a restite origin.

Conclusions

The Loch Sunart GCR site represents one of the finest examples worldwide of mid-crustal pluton emplacement. Fabrics and textures of the pluton clearly demonstrate the effect of active shearing during intrusion and crystallization of magma, which here was probably contemporaneous with movement within the Great Glen Fault system. The site is equally important in demonstrating succinctly the interaction of contemporaneous basic and granodioritic magmas during pluton emplacement, and also the incorporation of residual unmelted material from the source area (restite). The occurrence of basic rocks in all the granodioritic facies points to the continuous availibility of basic magma throughout the emplacement history of the pluton.

CNOC MOR TO RUBH' ARDALANISH (NM 367 186–360 160)

A. J. Highton

Introduction

The Ross of Mull pluton

The Ross of Mull pluton extends over an area of some 140 km^2, much of which lies offshore, forming skerries along the eastern coast of Iona

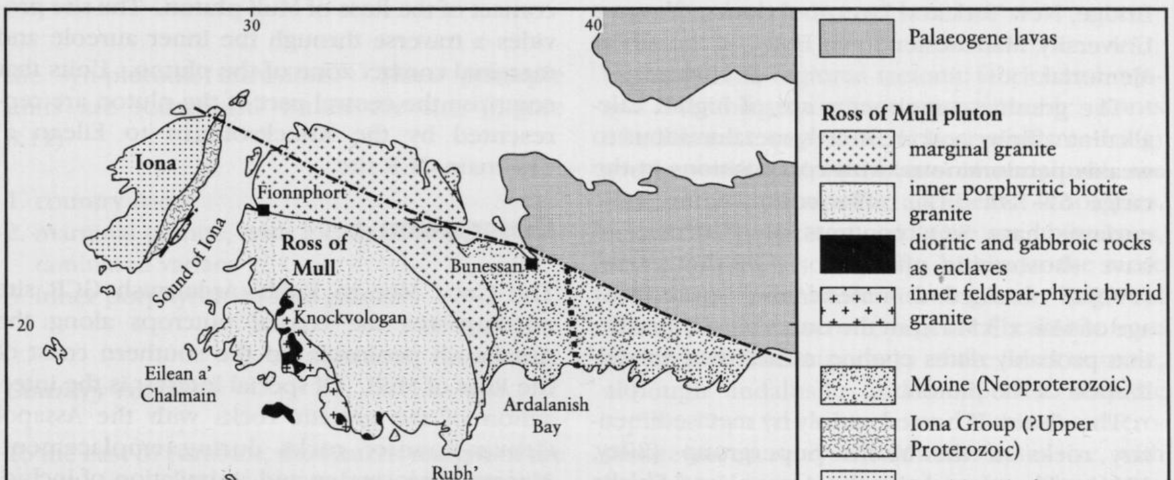


Figure 8.10 Map of the Ross of Mull pluton.

and the Torran Rocks (Cunningham-Craig *et al.*, 1911; Bailey and Anderson, 1925; Barber *et al.*, 1979). The pluton is mainly granitic, with a crudely concentric reverse zonation. Three discrete facies are identifiable within the land outcrop (on the basis of variations in biotite content), all with gradational internal contacts (Figure 8.10):

1. an outer non-porphyritic equigranular biotite granite, which is the most evolved part of the pluton; a xenolithic, two-mica contaminated variant forms small bodies along the pluton margin;
2. an inner pink K-feldspar-phyric biotite granite;
3. a heterogeneous hybridized variant of '2' that ranges from biotite granite to biotite granodiorite, and contains hybrid rocks and basic enclaves.

Little is known of the geology offshore, although the granites off eastern Iona and the Torran Rocks are similar to the outer facies.

The Ross of Mull granites have been quarried extensively in the past, particularly the outer non-porphyritic granite along the coast north of Fionnphort (Faithfull, 1995). The stone has been used for bridges, docks, lighthouses and other buildings throughout the world, as well as for ornamental stone. Noteable examples include Ardnamurchan Lighthouse, Westminster Bridge, New York and Liverpool docks, Glasgow University, Manchester Town Hall and the Albert Memorial.

The granitic components are of high-K calc-alkaline affinity, and are mostly metaluminous to weakly peraluminous, with compositions in the range 67–78% SiO_2. The rocks of the basic enclaves have SiO_2 contents of 45–55%, and have shoshonitic affinities. Halliday *et al.* (1979a) obtained a mineral/whole-rock Rb-Sr age of 414 ± 3 Ma from the outer biotite granite, that probably dates cooling rather than crystallization of the pluton.

The pluton is hosted mainly by metasedimentary rocks of the Moine Supergroup (Riley, 1966). These comprise the Assapol and Shiaba groups, thought to be lateral equivalents of the Glenfinnan and Morar groups of the mainland successions (Holdsworth *et al.*, 1987). Country rock xenoliths are present in all the facies and a relict stratigraphy is traceable through the pluton. To the west, the granite is in contact with low grade ?Upper Proterozoic metasedimentary rocks of the Iona Group. These overlie meta-igneous and metasedimentary rocks of the Archaean Lewisian Complex, with tectonically modified unconformity (Potts *et al.*, 1995).

The thermal overprint in the Moine rocks extends up to 3 km from the eastern margin of the pluton, but significant hornfelsing, marked by the incoming of andalusite, is found only within 500 m of the contact (Bailey and Anderson, 1925). Higher-grade assemblages containing fibrolite and sillimanite appear only at the pluton contact (Brearly, 1984). Regional metamorphic kyanite is metastable throughout much of the aureole (Bosworth, 1910; MacKenzie, 1949). Clough (in Bailey and Anderson, 1925) noted the occurrence of a small suite of hornfelsed microdioritic intrusions ('lamprophyres') close to the eastern margin, which pre-date granite emplacement. On Iona the aureole is generally less than 1 km wide.

Both the granite and the country rocks are cross-cut by a synplutonic suite of minor intrusions consisting of shoshonitic calc-alkaline lamprophyres (spessartite and kersantite) and porphyritic microgranodiorite. These intrusions are mostly sheets, with composite or multiple forms common. All are cut by, generally ESE-trending, camptonite and monchiquite dykes of Permian age (Beckinsale and Obradovich, 1973).

The Cnoc Mor to Rubh' Ardalanish GCR site demonstrates the form and nature of the eastern contact of the Ross of Mull pluton. The site provides a traverse through the inner aureole and marginal contact zone of the pluton. Units that comprise the central part of the pluton are represented by the Knockvologan to Eilean a' Chalmain GCR site.

Description

The Cnoc Mor to Rubh' Ardalanish GCR site encompasses the coastal outcrops along the Ardalanish peninsula on the southern coast of the Ross of Mull. Of special interest is the interaction of the granitic rocks with the Assapol Group country rocks during emplacement. Magmatic processing and assimilation of included metasedimentary material has resulted in a locally developed marginal hybrid granite. Here, enclaves and screens of Moine metasedimentary rocks are seen in various stages of incorporation into the host granite. Other notable features of the site are the aureole and

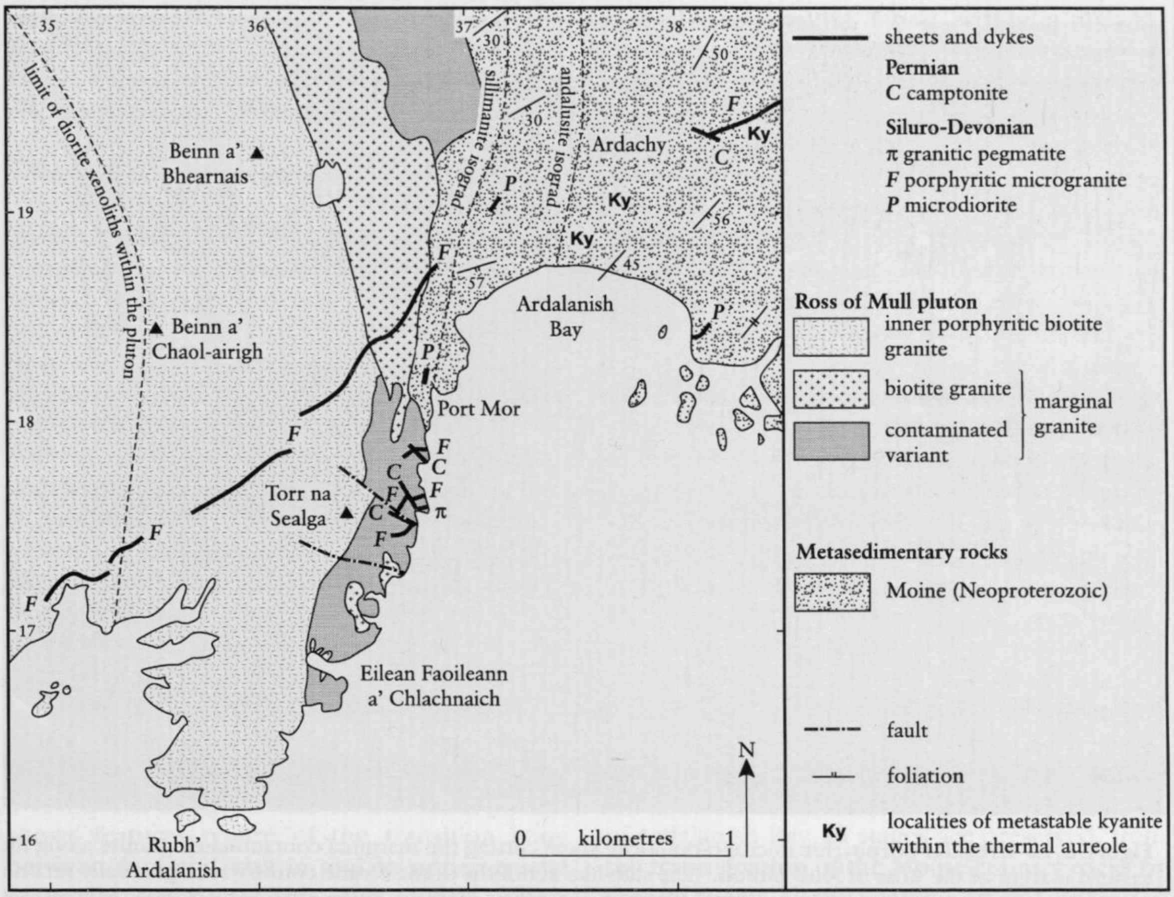


Figure 8.11 Map of the area around the Cnoc Mor to Rubh' Ardalanish GCR site, Ross of Mull pluton, adapted from BGS 1:50 000 Sheet 43 and unpublished work, University of Liverpool.

the syn-plutonic intrusions. Three principle units are recognized within the site (Figure 8.11):

1. country rocks
2. marginal granite, with locally developed contaminated variant
3. inner porphyritic biotite granite

Country rocks

To the east of Port Mor, the eastern margin of the granitic pluton is in contact with country rocks of the Assapol Striped and Banded Formation. These comprise variably interlayered beds of semipelite, psammite and minor pelite, with concordant ribs of calc-silicate rock. Both the metasedimentary rocks and the microdiorite intrusions within the envelope are hornfelsed. In the former, regional tectonic fabrics and mineral assemblages are barely recognizable. Knots of sillimanite (up to several centimetres long) and/or small porphyroblasts of andalusite are prominent in semipelitic and pelitic lithologies. Small dark crystals of cordierite are ubiquitous, and cordierite also replaces biotite in the more micaceous psammitic lithologies. Regional metamorphic muscovite is generally absent from the metasedimentary rocks of the inner aureole, although andalusite and/or fibrolite may be replaced by a late white mica. Within the microdiorite sheets recrystallization is extensive, with hornblende overgrown and replaced by a new red biotite.

Marginal granite

Of principal interest in this site is the occurrence of a zone of contamination, up to 200 m wide,

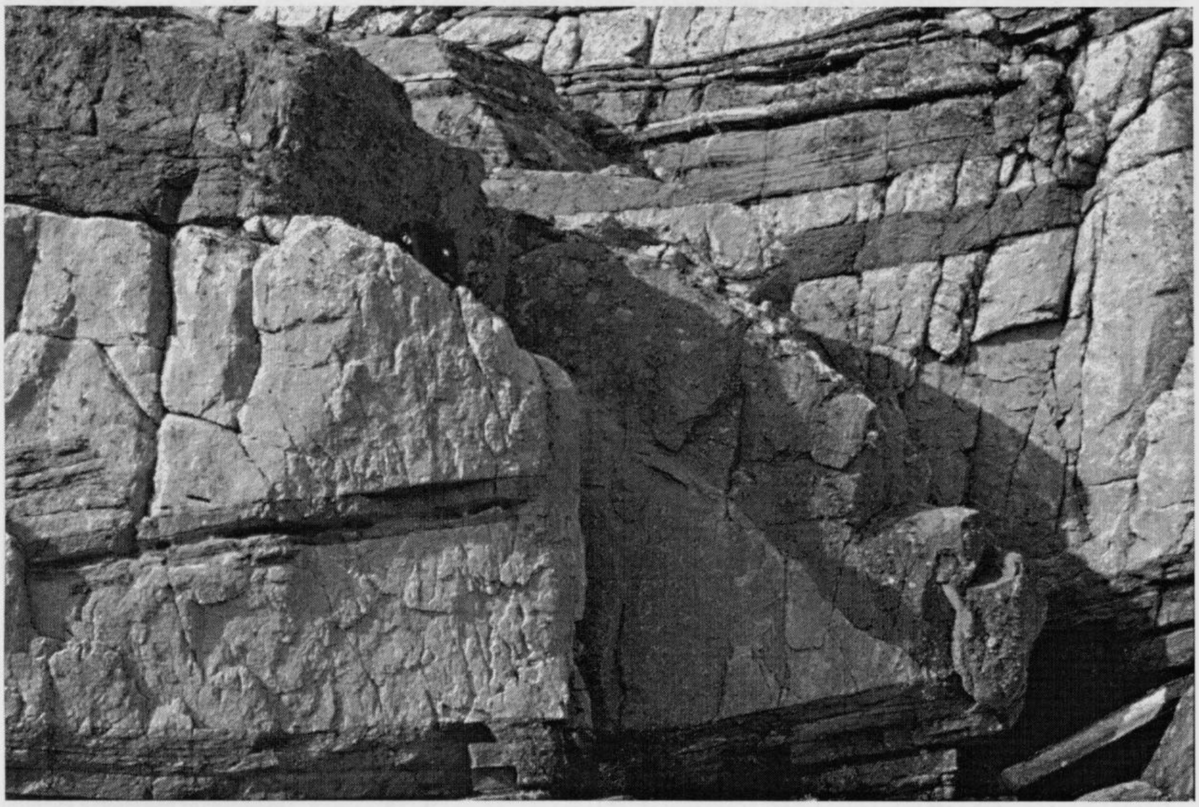


Figure 8.12 Irregular porphyritic microgranodiorite sheet cutting the marginal contaminated granite along the eastern margin of the Ross of Mull pluton. The slab-like xenoliths of the Moine country rock generally retain a pre-emplacement attitude in this marginal sheeted complex. Carraig Mhór (NM 3678 1762). (Photo: A.J. Highton.)

along the eastern margin of the pluton. This contaminated variant forms most of the outcrop of the marginal granite exposed along the eastern side of the peninsula between A' Bhualaidh and Eilean Faoileann a' Chlachanaich. The non-contaminated granite parent is seen only in exposures on Cnoc Mor, as a pale-pink, coarse-grained, equigranular biotite granite. The contaminated granite variant is marked by a decrease over several tens of metres in the pink colouration of the parent granite. Outcrops are commonly crowded with country rock xenoliths showing all stages of assimilation into the host. The contaminated granite is unusually quartz-rich and contains abundant mesocrysts of red-brown biotite, which contain inclusions of zircon and zoned dark-cored apatite. Muscovite is present but is not a primary mineral. Pods and small masses of granite pegmatite are locally common. A large sheet of coarsely crystalline pegmatite at 3677 1760, presents a fine example of macroscopic microcline perthite.

The contact with Moine rocks is essentially a sub-horizontal sheeted complex of interdigitating granite and country rock. The envelope is gradational over a few tens of metres, from country rocks containing granite sheets concordant with the prominent foliation, into granite with screens of metasedimentary rocks. The marginal granite carries abundant rafts, up to 250 m long (364 172) and slab-like xenolithic blocks (Figure 8.12). An outcrop (at 3673 1804) contains enclaves in varying states of assimilation from little altered angular slabs to rounded enclaves. The latter are enclosed by a reaction corona of leucocratic granodiorite. Locally the contaminated granite contains a nebulous mica fabric or schlieren of biotite-rich restite. These schlieren typically wrap around included blocks. K-feldspar megacrysts are common in many partially assimilated enclaves. These overgrow both the relict metamorphic fabrics in the enclaves and the contacts with the granite host.

Sheets of porphyritic microgranodiorite, generally dipping NW at 15–40°, cut all facies of the granite and country rocks. These irregular sheets, display necking and side-stepping typical of synplutonic minor intrusions (Figure 8.12).

Inner porphyritic biotite granite

Much of the site on the Ardalanish peninsula comprises a K-feldspar-phyric biotite granite facies. This component is generally a pink, coarse-grained biotite monzogranite, with abundant megacrysts, up to 5 cm long, of pink perthitic microcline. This is well exposed in low rounded outcrops of the Rubh' Ardalanish area. The boundary of the porphyritic biotite granite with the marginal granite is generally transitional over several tens of metres. Mica schlieren are, however, recognizable within the outer facies at some distance from the main outcrop of contaminated marginal variant (359 162). On A' Bhualaidh, the contact with the marginal granite is sharp.

Interpretation

This eastern margin of the Ross of Mull pluton shows features typical of the transition zone between roof and wall in mid to upper crustal granite intrusions (Fowler *et al.*, 1995), which helps to explain the relatively wide thermal aureole. In section, the contact is low to moderately inclined to the east, and is irregular with brittle-looking metre-scale angular steps. Pre-existing regional deformational structures in the envelope do not appear to control the overall form of the contact, and are truncated mostly at a high angle. However, low-angled sheets have exploited foliation planes along much of the margin. Here country rock blocks are typically angular slabs with minimal rotation from their original orientation in the envelope. Away from this sheeted margin, included blocks of country rock are commonly separated by granite with locally prominent biotite-rich schlieren and banding. A tectonic origin for this mica fabric is unlikely. Evidence of strain-induced recrystallization or ductile thinning of beds within included material is absent. Further, the synplutonic minor intrusions cut across internal structures in the pluton, but close to the margin take on a stepped form similar to that of the contact. Thus, the schlieren more likely derive from incomplete processing and incorporation of envelope material during intrusion, resulting in a biotite-rich restite fabric within a hybrid. Hence the areas of contaminated hybrid granite preserve clues to part of the pluton emplacement mechanism.

The emplacement process along this eastern margin was probably initiated by wall rock assimilation, but gave way to penetration and stoping of the envelope. Deflection of the schlieren fabric around included blocks points to foundering of blocks from the roof into a partially crystalline granite hybrid. The transitional boundary into the porphyritic biotite granite points to relative homogenization in the main part of the magma body. Preservation of the contaminated marginal rocks may well be fortuitous, reflecting local ponding within an irregularity in the roof or wall.

Conclusions

This GCR site is of national importance as a representative of the Ross of Mull pluton, which provides one of the most definitive examples of passive emplacement with assimilation of country rock in the Caledonian plutonic suites. Within the coastal outcrops on the western side of Ardalanish Bay, all stages are preserved, from the impregnation of the Moine country rocks by granite sheets, to the spalling off and sinking of slabs and blocks of country rock into the granite magma (stoping). Assimilation of metasedimentary material into the marginal granite resulted in the development of a contaminated hybrid granite, present at the pluton–country rock contact throughout most of the site. Localized ponding of fluids in the magma led to the crystallization of pegmatite. The complex sub-horizontal sheeted margin is unlikely to reflect the pluton form, but lies within the transition between the roof and wall of the intrusion.

KNOCKVOLOGAN TO EILEAN A'CHALMAIN (NM 309 175–309 204)

A. J. Highton

Introduction

The coastal exposures on the eastern side of Erraid sound, on Eilean Dubh and on Eilean a' Chalmain, which comprise this GCR site, encompass the central part of the Ross of Mull granitic

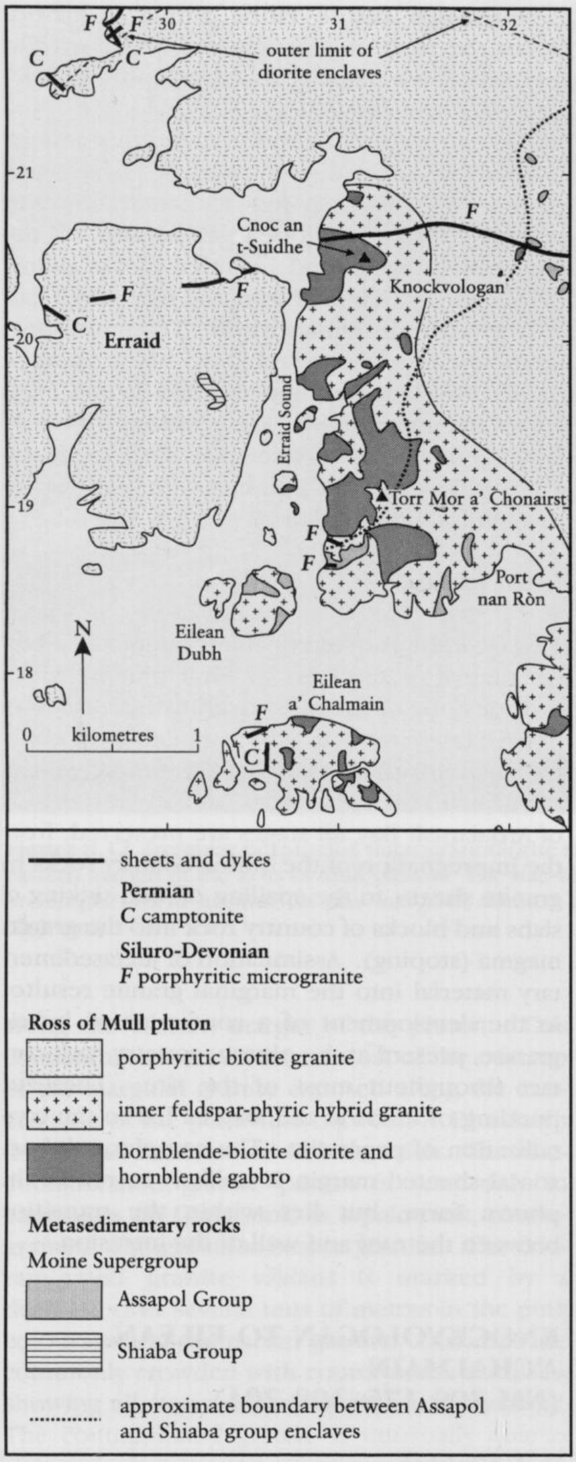


Figure 8.13 Map of the area around the Knockvologan to Eilean a' Chalmain GCR site, Ross of Mull pluton, adapted from BGS 1:50 000 Sheet 43 and unpublished work, University of Liverpool.

pluton (Figure 8.13). The general features of the pluton are described in the Cnoc Mor to Rubh' Ardalanish GCR site report. Here, heterogeneous hybrid granitic rocks contain chilled enclaves of gabbroic and dioritic rocks ('appinites'). These enclaves have high-K basalt to basaltic andesite compositions and themselves contain mafic microgranular enclaves and xenocrysts. The hybrid rocks grade over several hundreds of metres into the inner porphyritic biotite granite of the Ross of Mull pluton, which still contains mafic enclaves up to 3 km beyond the site. Of special interest are textures and lithologies resulting from the generation of these hybrid rocks through the incorporation of the basic to intermediate material into the granitic host. The site also preserves a 'ghost stratigraphy' of the Moine country rocks, which can be traced through the granitic rocks in the metasedimentary xenoliths.

Description

Although dioritic rocks form a small component of the Ross of Mull pluton, their abundance within this GCR site is considerable. The basic enclaves range in size from a few centimetres to several hundreds of metres and the largest discrete mass of basic rock comprises most of Eilean a' Chalmain. Rocks within this outcrop are heterogeneous, ranging from medium-grained diorite to coarse-grained appinitic monzodiorite characterized by poikilitic crystals of orthoclase and pale-coloured biotite. The outcrop is cut by numerous sheets and apophyses of biotite granite, but with little development of hybrid rocks.

Exposures on the small island to the north of Eilean Dubh (at 3064 1894) and on the west-facing shore of Erraid Sound (at 3077 2012) provide good examples of the mafic enclave-rich hybrid granitic rocks and of their heterogeneous textures. The hybrid host rock is predominantly a biotite-rich granite (± rare primary amphibole), with a significant accessory mineral component (titanite, allanite and magnetite). However, there is a range of compositions from mafic granodiorite to quartz-diorite. The enclaves range in size from a few centimetres to several metres across, and in composition from fine-grained hornblende gabbro or microgabbro to microdiorite. Their distribution is variable, but locally they comprise up to 10% of the granite. Larger enclaves are typically surrounded by

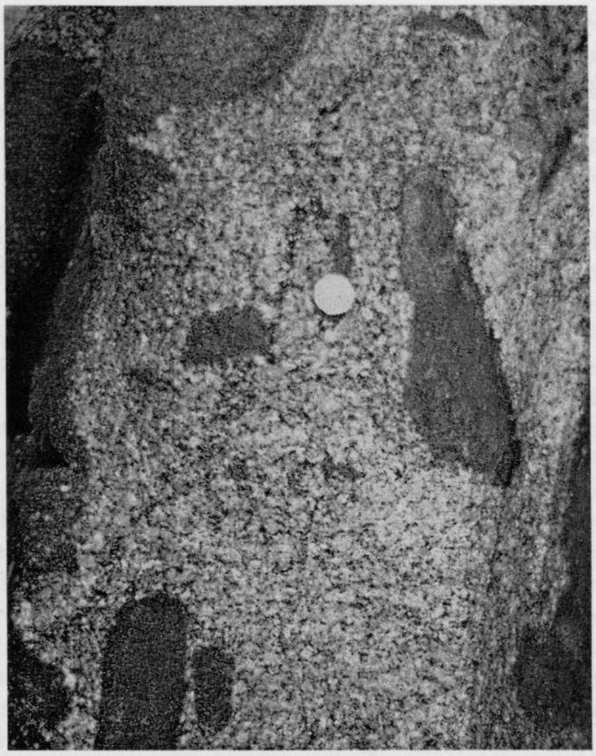


Figure 8.14 Small meladiorite ('appinite') enclaves enclosed by a hornblende-biotite granodiorite hybrid host, centre of the Ross of Mull pluton, west of Port nan Ròn (NM 3124 1858). (Photo: A.J. Highton.)

numerous smaller fragments (Figure 8.14). Most are rounded in form, and commonly show finely lobate contacts with their host. The contacts vary from sharp with fine-grained 'chilled' margins, to diffuse. Where contacts are diffuse, the enclaves are either enclosed by discrete coronas of hornblendic quartz-diorite or grade over several tens of centimetres into the host biotite-rich granite. Quartz-diorite with small hornblende-rich aggregates similar to the corona material also occurs as small rounded blobs within the hybrid granite. Veining or development of small areas of net-veined hybrid rocks are common. The veins, of fine-grained leucotonalite to microgranodiorite, cut both host and enclaves. Glomerocrysts of quartz and plagioclase are common in the hybrid rocks, while K-feldspar mesocrysts occur in all lithologies.

A weak to moderately developed mineral fabric is present in most of the igneous rocks of the site. This partially wraps the enclaves, which take on an ellipsoidal shape in areas where the fabric is strongly developed.

The metasedimentary inclusions in the granite define a 'ghost stratigraphy'. K-feldspar-rich arkosic psammites and finely laminated psammites of the Upper Shiaba Psammite crop out within the northern part of the GCR site, (e.g. 3095 1952), and on islands in the Erraid Sound, while striped psammites and semipelites of the Assapol Group occur elsewhere. The xenolith populations have a clearly definable distribution, with little intermixing. Structures and fabrics in the larger inclusions, for example at Cnoc an t-Suidhe, to the SW of Torr Mor a' Chonaist, at Port nan Ròn and on Eilean Dubh, are comparable in orientation to those in the country rocks. Hence, these are probably close to in-situ roof pendants. Examples of thermal overprinting, partial melting and assimilation into the granite are common. Within the inclusions of Assapol Group rocks to the west of Port nan Ròn, sillimanite forms knots that both overprint all fabrics, and mimetically replace the biotite that forms crenulation cleavages axial planar to minor folds in semipelitic lithologies.

Interpretation

The age of the mafic enclaves and meladiorite bodies within the Ross of Mull pluton has been interpreted in several ways. Cunningham-Craig *et al.* (1911), suggested that they represent a disrupted diorite complex intruded as a precursor to emplacement of the pluton. Recent studies (R. H. Hunter, University of Liverpool, pers. comm.) suggest that the lobate fine-grained 'chilled' margins to many enclaves result from quenching during the interaction of penecontemporaneously emplaced basic to intermediate and acid magmas. Physical mixing, with thermal equilibration between the magma types, resulted in the formation of the heterogeneous hybrid rocks. The presence of enclaves of similar composition to these hybrid rocks within the main porphyritic biotite granite indicates local dispersion and mingling of the hybrid liquids. The more basic magmas are probably contemporaneous with the suite of calc-alkaline lamprophyre and microdiorite dykes present within the envelope. However, the linear trains of enclaves recognized in other Caledonian plutons, e.g. Strontian (see the Loch Sunart GCR site report) have not been recorded.

The origin of the internal foliation is equivocal. The enclaves show little evidence of significant deformation indicative of high syn-emplacement strains. Hence the fabric may be magmatic in part.

The distribution pattern of the metasedimentary xenoliths follows predicted stratigraphical lines. The lack of fragmentary dispersal, with only local intermixing, and the lack of significant re-orientation suggests a passive emplacement mechanism into the envelope and close proximity to the roof of the pluton.

Conclusions

The Ross of Mull pluton is notable among the Caledonian plutons for the preservation of one of the finest examples of 'ghost' country rock stratigraphy within an intrusion. This demonstrates that the pluton was intruded through a process of passive emplacement with little disruption of the metasedimentary country rocks. The 'ghost stratigraphy' is best preserved within this GCR site, which imparts an international significance to the site and to the pluton as a whole. The hybrid rocks featured in this site provide an example of the co-existence of basic to intermediate and granitic magmas in the pluton. Features are typical of magma mixing and mingling, with dispersed rounded enclaves of both basic and hybrid material in the porphyritic biotite granite host. It is considered that the basic and granitic magmas were intruded at the same time and their interaction has given rise to zoning within the pluton, with more basic rocks passing outwards to more acid rocks (reverse zoning).

BONAWE TO CADDERLIE BURN (NN 008 336–038 385)

A. J. Highton

Introduction

The Etive pluton

Like many plutons of the late Caledonian Argyll and Northern Highlands Suite, the Etive pluton is composite, ranging from diorite through to monzogranite (Bailey and Maufe, 1916; Kynaston and Hill, 1908; Anderson, 1937; Batchelor, 1987). It was emplaced at *c.* 400 Ma (Pidgeon and Aftalion, 1978; Clayburn *et al.*, 1983) into metasedimentary and meta-igneous rocks of the Dalradian Supergroup. This large elliptical intrusion, covering an area of some 300 km², comprises four discrete intrusive phases. In order of emplacement these are the Quarry intrusion, the Cruachan facies, the Meall Odhar facies and the central, Starav facies (Figure 8.15).

An accompanying NE-trending swarm of syn-plutonic dykes, the Etive dyke-swarm, consists mainly of porphyritic microdioritic and microgranodioritic lithologies, and contains sub-suites that either cut or are truncated by the main granitic facies. The pluton is spatially associated with extrusive rocks of the Lorn plateau to the SW and the Glen Coe caldera volcano to the north (see Chapter 9), but it is unlikely to be the source of their magmas. Pressure estimates from the metamorphic aureole indicate a high crustal, subvolcanic, emplacement level at *c.* 3–6 km (Droop and Treloar, 1981).

The Bonawe to Cadderlie Burn GCR site

This site, along the western shore and succeeding hills of Loch Etive, includes the extensive quarries at Bonawe, which were worked historically for paving sets and latterly for hard rock aggregate. The site provides a broad traverse from the country rock envelope through most of the principle components of the Etive pluton

(Figure 8.16). This illustrates the range of lithologies and their sequence of emplacement, from the outer xenolith-rich monzodiorites of the Cruachan facies to the monzogranitic rocks of the inner, Starav facies (Anderson, 1937). The satellitic Quarry intrusion is not present here, but is represented by the Cruachan Reservoir GCR site. Synplutonic dykes are also present. The country rocks within the site are assigned to the Bonawe Succession, a possible correlative of the Easdale Slates within the lower Argyll Group of the Dalradian Supergroup (Litherland, 1980). These country rocks are the predominant enclaves in the outer part of the Cruachan facies, often occurring as large screens or roof pendants.

Description

Margin and envelope

On the south-western slopes of Beinn Duirinis above Bonawe, the irregular NW-trending contact of the pluton is traceable in almost continuous exposure, (e.g. 0065 3385). Along much of the western edge the pluton margin is a sheeted complex. Within the GCR site it is sharp and mainly sub-vertical but locally it dips inwards at a steep angle. To the SE, the country rocks of fine-grained semipelite and black slates of the Bonawe Succession form small outcrops on the shore at Bonawe (0065 3353). These rocks reached biotite grade during the Caledonian regional metamorphism. On emplacement of the pluton, there was extensive recrystallization of the country rocks, with macroscopic poikiloblasts of cordierite and andalusite overgrowing the tectonic fabrics. Close to the pluton contact (0068 3374) the host rocks became hornfelsed, with bedding and the regional tectonic fabrics largely obliterated.

Cruachan facies

Much of the GCR site between Bonawe and Cadderlie lies within the Cruachan facies (Figure 8.16). Of principal interest is a marginal, variably foliated, enclave-rich monzodioritic variant, that forms much of a 1 km-wide outcrop to the SE of Lag Choan (027 340). In the lower level of the current workings in Bonawe Quarry at 0215 3365, rafts and xenoliths of Bonawe Succession

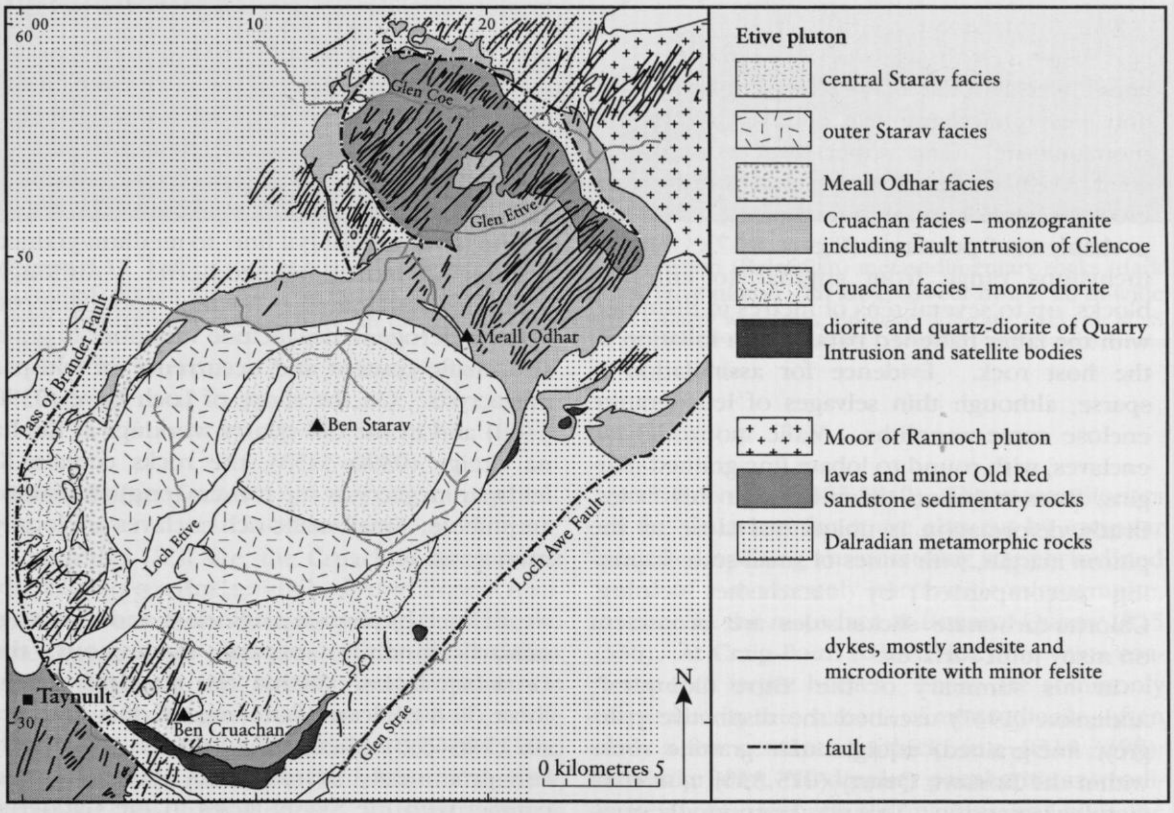


Figure 8.15 Map of the Etive and Glencoe complexes, after Anderson (1937) and Batchelor (1987).

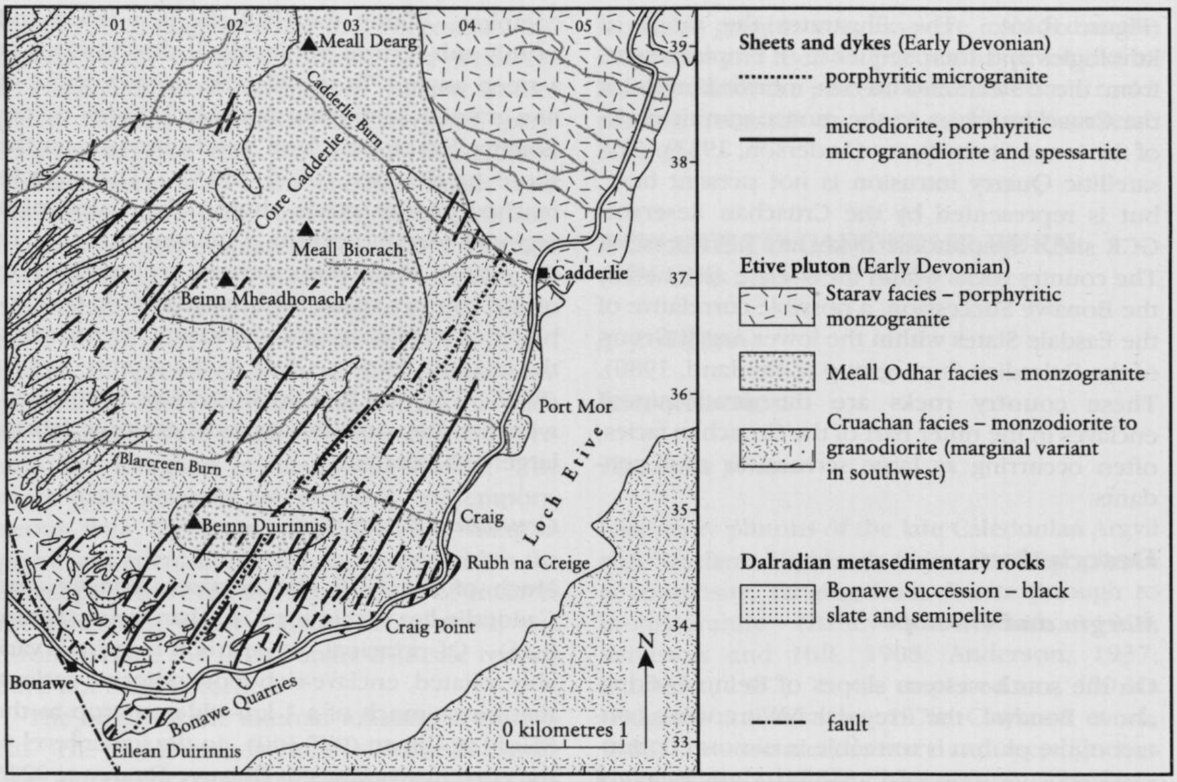


Figure 8.16 Map of the area around the Bonawe to Cadderlie Burn GCR site, Etive pluton, adapted from BGS 1:50 000 Sheet 45W.

rocks, weakly foliated porphyritic microdiorite, and mafic microgranular enclaves crowd the monzodiorite. The upper level workings (at 0214 3370) expose large spalled country rock blocks, several hundred metres long, which are probably roof pendants (Figure 8.17). Smaller inclusions range from angular to elliptical blocks, up to several tens of metres in diameter, with the latter flattened parallel to a foliation in the host rock. Evidence for assimilation is sparse, although thin selvages of leucogranite enclose some xenoliths. Mafic monzodioritic enclaves, with round to lobate fine-grained margins, form inclusion trains through this facies. Brittle deformation is ubiquitous close to the pluton margin, with zones of small-scale fracturing accompanied by cataclasite veining. Chlorite-carbonate slickensides are prominent on many joint surfaces.

In his summary of the 'Etive Complex', Anderson (1937) ascribed the distinctive pale-grey, fine-grained, equigranular granitic rocks within the Bonawe Quarry (015 335) to a small marginal intrusion. This was purportedly separated from the main intrusion by a screen of metasedimentary rocks. This leucocratic biotite granodiorite is now regarded as a marginal phase of the Cruachan facies. Nebulous patches and net-veins of leucogranodiorite represent local heterogeneities.

The inner variant is a fine- to medium-grained hornblende-biotite monzodiorite. Although generally equigranular, textural and compositional heterogeneities include variations in grain size, mafic content and occurrence of feldspar megacrysts. On the shore of Loch Etive (0390 3460) and in the old quarry workings at Rubha na Creige (0390 3453), the rocks contain K-feldspar megacrysts (up to 1 cm long) and minor amphibole. Small mafic-rich enclaves are locally numerous.

A steep inwardly dipping, margin-parallel fabric, defined by aligned plagioclase and ferromagnesian minerals, occurs throughout the Cruachan facies. Within the marginal variant there is significant flattening of the enclaves (0215 0363). Although the foliation is generally less prominent inwards, rocks adjacent to the contact with the Starav facies in the Cadderlie Burn (0440 3709) contain a well-defined fabric.

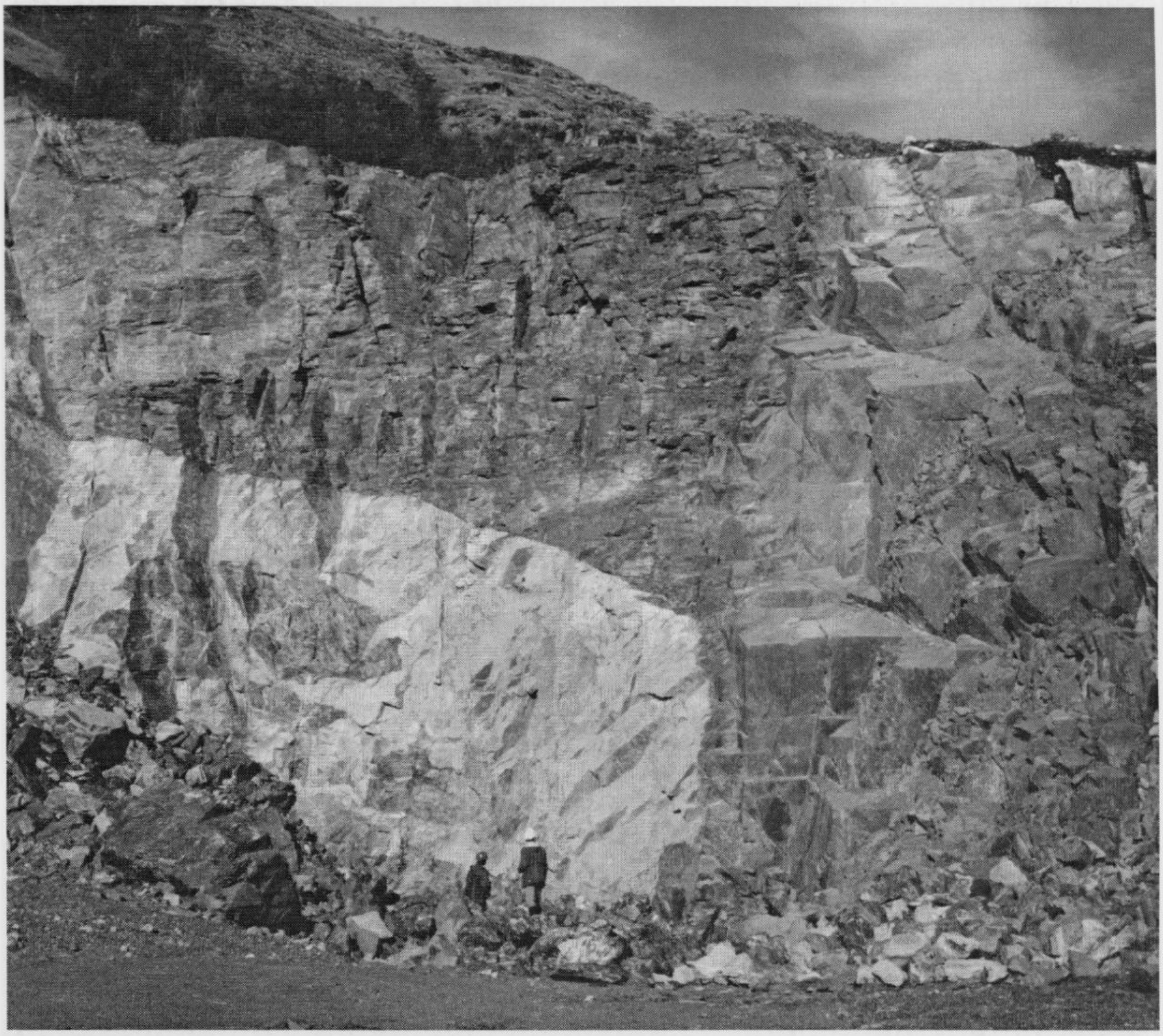


Figure 8.17 Raft or roof pendant of hornfelsed Bonawe Succession (Dalradian) metasedimentary rocks (dark coloured) within the marginal variant of the Cruachan facies, Etive pluton. All are cross-cut by a *c.* 20 m-wide dyke of porphyritic microgranite (to the right of the photo). Quarry workings, Bonawe. (Photo: BGS no. MNS 4849.)

Meall Odhar facies

Within this GCR site, the Cruachan facies is cut by two large shallow-dipping intrusions comprising weak to moderately porphyritic, fine- to medium-grained pink granite, the Meall Odhar facies (Figure 8.16). A small body crops out on the summit of Beinn Duirinnis (021 347), while the slopes of Coire Cadderlie (035 385) and Meall Biorach (027 374) lie within a shallow, irregular, NE-dipping sheet. This intrusion is truncated by the Starav facies along a sharp sub-vertical contact (0383 3840). The monzodiorites of the Cruachan facies are also cut by irregular zones comprising anastomosing steeply inclined veins of a moderately porphyritic microgranite, as seen in the main face at Bonawe Quarry (015 335). At Craig Point (0307 3402) the veins coalesce into larger bodies. These are commonly separated by thin screens of monzodiorite, often only a few centimetres thick, (e.g. 0314 3398). At Craig Point, NE-dipping porphyritic microdiorite sheets, with chilled margins, cut both the Cruachan and Meall Odhar facies.

Starav facies

Only the outer porphyritic variant of the Starav facies lies within the GCR site (Figure 8.16). As seen on the NE flank of Meall Dearg (035 390), this variant is typically a coarse-grained pink-grey monzogranite, with conspicuous K-feldspar megacrysts up to 3 cm long. The rocks are hornblende- and biotite-bearing, with conspicuous phenocrysts of titanite, although the mafic content is generally less than 10%. Mafic-rich microgranular enclaves, up to 4 mm, comprising amphibole + biotite + opaque minerals ± pyroxene, are common. The K-feldspar megacrysts are numerous in the outer part of the intrusion, but decrease inwards in both size and abundance (Anderson, 1937). To the NW of Cadderlie (0414 3736), the marginal rocks are non-porphyritic up to 15 cm from the contact with the Cruachan facies. Elsewhere, the K-feldspar megacrysts overgrow a ubiquitous weak, steep inward-dipping margin-parallel foliation.

Minor Intrusions

The plutonic rocks of the GCR site are cut by numerous NE-trending dykes and some sheet-like intrusions (Figure 8.16). The swarm consists mainly of microdiorite and porphyritic microgranodiorite (formerly termed 'porphyrites'), but also includes meladiorite ('appinite'), spessartite, olivine kersantite and quartz-phyric microgranite (formerly termed 'quartz-porphyries'). Sub-suites include those that:

a. transgress all facies of the pluton;
b. cut all the pre-Starav facies;
c. are truncated by the Cruachan facies.

A pink quartz-phyric microgranite dyke cropping out in the Cadderlie Burn (0431 3716) provides the only example in the GCR site of an intrusion cutting the Starav facies, but does not extend much beyond the contact with the Cruachan facies. From here this dyke is traceable south-westwards to the main quarry at Bonawe, and on the southern flank of Beinn Duirinis (018 342) it cuts a microdiorite dyke (type b). Cross-cutting relationships within the minor intrusive suite are well seen in the new quarry workings (0214 3370). Here also, a *c.* 20 m-wide porphyritic microgranite intrusion (Figure 8.17) contains rounded microdiorite xenoliths. In most porphyritic intrusions the phenocrysts have a margin-parallel alignment. Examples of hornfelsed pre-Cruachan facies minor intrusions crop out on the south-facing slopes above Kenmore (0052 3393).

Interpretation

The Etive pluton is an excellent example of multiple pulse emplacement (Anderson, 1937; Frost and O'Nions, 1985; Batchelor, 1987). Overall, the pluton is one of the least evolved of the Argyll and Northern Highlands Suite intrusions, with initial $^{87}Sr/^{86}Sr$ values ranging from 0.7043 to 0.7068 (Clayburn *et al.*, 1983; Frost and O'Nions, 1985). The isotopic data has been variously interpreted as providing: (a) evidence for either the recycling of lower continental crustal material during magmatic evolution, with significant assimilation of country rock (Frost and O'Nions, 1985); or (b) the incorporation of a substantial component of older continental crust (Hamilton *et al.*, 1983) or a mantle component (Thirlwall, 1986). The Cruachan and Starav facies derive from different parental magmas; the latter having a 'juvenile' signature (Plant *et al.*, 1985).

The Cruachan facies was historically thought to comprise two lobes, predominantly monzodioritic in the south and monzogranitic in the north (Anderson, 1937). These compositional differences have been attributed subsequently to tilting of the intrusion, exposing more evolved rocks to the north (Brown, 1975), although there may be two separate intrusions (Barritt, 1983). Compositional variations within the Cruachan facies are consistent with the intrusion of successive pulses from essentially the same magma source (Batchelor, 1987). This suggestion is also reinforced by compositional variations within those members of the Etive dyke-swarm, that are broadly contemporaneous with emplacement of the Cruachan facies. The presence of mafic-rich enclaves alludes to the availability of contemporaneous basaltic magma during emplacement of the Cruachan facies. Monzodioritic enclaves within the outer felsic variant, point to mingling of these basaltic magmas with their granitic host, leading to localized hybridization.

The irregular sheet-like intrusions of the Meall Odhar facies lie within the upper parts of the Cruachan facies while the vein complexes pervade differing levels. Batchelor (1987) suggested that the Meall Odhar facies intrusions are precursors to the emplacement of the Starav facies, although the conduit is no longer recognizable. However, rocks of the Meall Odhar facies are cut by minor intrusions consanguineous with the Cruachan facies magmas. Published geochemical analyses show that Meall Odhar facies rocks are consistently more evolved than the Starav facies (Rb/Sr 1.1–8.5 and 0.12–2.8, respectively; cf. Clayburn *et al.*, 1983; Batchelor, 1987), with significantly lower levels of Rb and Sr. This corroborates the suggestion of Clayburn *et al.* (1983), on isotopic evidence, that a new magma batch was introduced after the emplacement of the Meall Odhar facies. The occurrence of high-level residual fractionation melt bodies is a feature of other Caledonian plutons, e.g. Cairngorm and Monadhliath (Harrison, 1987a; Highton, 1999), and may provide a solution for the origin and distribution of the Meall Odhar facies. Hence it is unlikely that the Meall Odhar facies simply represents a tapping of contemporaneous Starav facies magmas.

Reverse compositional zonation in the pluton from outer felsic-rich to inner mafic-rich phases has been cited as evidence for cauldron subsidence (Batchelor, 1987; following Anderson, 1956). The abundance of xenoliths, rafts, screens or roof pendants is characteristic of carapace foundering into the magma body, with the form and size of xenolithic material demonstrating the varying stages of stoping. However, Jacques and Reavy (1994) interpret the margin-parallel foliation as a pre-full crystallization fabric. It is argued that this fabric is a consequence of high-level in-situ 'ballooning' contemporaneous with shearing on NE-trending faults. The flattening of enclaves and en echelon pull-aparts seen at Bonawe are consistent with shearing about a steeply inclined axis. Hence evidence of plastic strain during the later stages of crystallization would support the case for synmagmatic transpressional shear rather than simple block let down.

Conclusions

The Bonawe to Cadderlie Burn GCR site is of national and international importance for the cross section through the Etive pluton, which contains examples of differing mantle- or lower crustal-derived magmas. The site embraces some of the finest evidence of upper crustal, multiple pulse pluton emplacement and also illustrates important evidence for dykes that were intruded into the larger bodies of magma while they were still cooling. Fabric evidence at outcrop is consistent with intrusion via deep crustal fractures into an active shear environment. The magma conduit may well have developed at the confluence of long-lived basement fractures and late Caledonian shear zones. Space was created for pluton emplacement by means of fracturing of the metasedimentary envelope and foundering of large blocks into the magma (stoping).

CRUACHAN RESERVOIR (NN 077 285)

A. J. Highton

Introduction

To the north of the Cruachan hydroelectric power station, outcrops along the Pass of Brander and on the SE flanks of Ben Cruachan provide a traverse through the metasedimentary envelope and marginal facies of the Etive pluton. This large elliptical pluton comprises four discrete intrusive phases; in order of emplacement these are the Quarry intrusion, the Cruachan facies, the Meall Odhar facies and the central, Starav facies (Figure 8.15) (see the Bonawe to Cadderlie Burn GCR site report). The envelope and complex contact relationships along this southern margin of the pluton, first described by Kynaston and Hill (1908), are well displayed within this GCR site. The outer margin comprises rocks of the Cruachan and Meall Odhar facies, similar to those documented within the Bonawe to Cadderlie Burn site. The inner, Starav facies, which is well displayed at the Bonawe to Cadderlie Burn site, is not represented at the Cruachan Reservoir site. Here also, an apparently down-faulted block of andesitic lavas, the Beinn a' Bhuridh screen, separates an arcuate satellite body, the Quarry intrusion, from the main body of the pluton. Within the Quarry intrusion, assimilation of calcareous metasedimentary rock xenoliths has produced some unusual hybrid rocks (Nockolds, 1934).

The Cruachan Reservoir GCR site encompasses the Cruachan pump storage system, part of the Loch Awe hydroelectric scheme (Figures 8.18 and 8.19). Excavations for the dam construction and the modification of water courses reveal details of the contact relationships

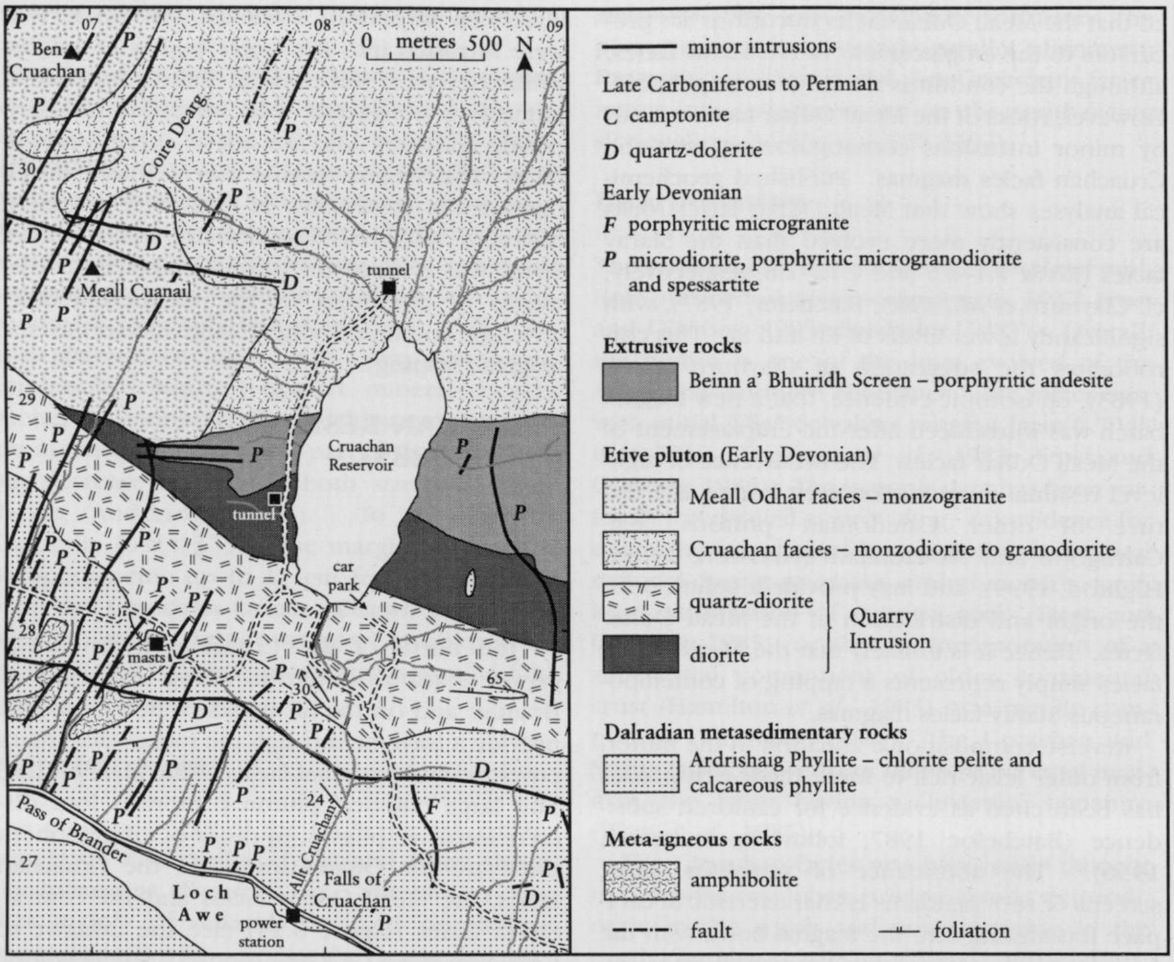


Figure 8.18 Map of the area around the Cruachan Reservoir GCR site, Etive pluton, adapted from BGS 1:50 000 Sheet 45E.

between the Etive pluton and its envelope. Detailed geological information was also obtained during the construction of underground tunnels, aqueducts and the power station (Knill, 1972).

Description

Margin and envelope

Much of the pluton envelope within the GCR site comprises metasedimentary rocks of the Ardrishaig Phyllite (Argyll Group, Dalradian Supergroup). These comprise finely interlayered black or purple chloritic phyllites and calc-silicate rocks, with thicker bands of impure metalimestone and calcareous quartzite. Close to the contact with the Quarry intrusion, the phyllites become hard splintery hornfelses, in which the regional deformational fabrics are poorly preserved. Biotite, as small porphyroblasts or aggregates, is the most common thermal aureole mineral, with rare cordierite spots. Within 200 m of the intrusion the calcareous rocks contain a contact metamorphic assemblage of pale-green diopsidic pyroxene, garnet, epidote and amphibole.

Quarry intrusion

This arcuate satellite intrusion consists of diorite and quartz-diorite variants. Both are represented within the GCR site (Figure 8.18). Only the quartz-diorite is in contact with the metasedimentary rocks of the envelope. The contact is discordant to the foliation in the host Ardrishaig Phyllite and has a steep outward dip, which is seen in the Allt Cruachan. Here, the quartz-diorite at the intrusion margin is fine grained but elsewhere, (for example at 0775 2813) and in the access road to the dam, it is commonly medium to coarse grained. It comprises phenocrysts of plagioclase, up to 1.5 cm long, and brown amphibole with interstitial quartz and K-feldspar. Country rock xenoliths in varying stages of assimilation are common, often enclosed by a heterogeneous quartz-rich hybrid granodiorite (0819 2804).

The diorite is finer grained than the quartz-diorite, with pyroxene phenocrysts, up to 8 mm long, as the predominant mafic mineral. A green amphibole occurs both as small phenocrysts and as aggregates, with biotite, after pyroxene. The contact between the two dioritic variants is transitional, for example along the shore of the reservoir (0785 2030). A margin-parallel pre-full crystallization fabric is present throughout the intrusion, but is most conspicuous in the coarser-grained rocks.

Beinn a' Bhuridh screen

The augite-hornblende andesites of the Beinn a' Bhuridh screen form the conspicuous crag (at 0775 2868), and crop out on the access track (at 0785 2870) and on the shore of the reservoir (Figure 8.18). A steeply dipping outer contact with the Quarry intrusion is exposed close to the tunnel entrance, west of the reservoir (0783 2865), and in the slopes above. The inner contact with marginal rocks of the main pluton (Cruachan facies) is not found within the site, and can only be inferred from elsewhere (cf. Anderson, 1937). However, the lavas are clearly hornfelsed and are commonly altered from dark-grey to a greenish colour. In outcrops to the west of the reservoir the lavas are commonly vesicular, the voids being infilled with quartz and/or chlorite. Here, fragments and small blocks of 'quartzite', up to 10 cm across, are also present.

Cruachan facies

Rocks of the Cruachan facies, which comprise the outer part of the main Etive pluton, form the outcrops close to the northern tail race entrance (0827 2946), on the NE-facing slope of Meall Cuanail (0775 2953), and in the burn emanating from Coire Dearg (0768 2972). Rocks of this facies cross-cut and vein rocks of the Quarry intrusion. The Cruachan facies comprises coarse-grained, pale pink-grey hornblende-biotite monzodioritic to granodioritic rocks, and is similar to the inner variant described from the Bonawe to Cadderlie Burn GCR site. Large crystals of biotite and small phenocrysts of green hornblende are the predominant mafic minerals in these rocks. The amphibole also occurs in mafic aggregates, up to 1 cm in diameter, with biotite, opaque minerals and rare pyroxene. Titanite is conspicuous as small deep-pink crystals. A pre-full crystallization fabric is ubiquitous, but is most intense at the pluton margin.

Within the tail race tunnel of the hydroelectric scheme, the monzodiorites of the Cruachan facies are cross-cut by veins of K-feldspar megacrystic hornblende-biotite granodiorite. This lithology may be a correlative of the marginal variant seen within the Bonawe to Cadderlie Burn GCR site. The mafic content of these rocks is variable, although mostly less than 15%. Biotite is predominant, while amphibole commonly occurs within small, 1–2 mm, mafic microgranular aggregates with titanite, magnetite and biotite.

Meall Odhar facies

This facies forms the twin summits of Ben Cruachan (Figure 8.19) and slab-like outcrops along the S-trending ridge from Meall Cuanail (072 288), where it imparts a characteristic pink colour to the ground. The facies comprises a fine- to medium-grained, equigranular, K-feldspar-phyric monzogranite. K-feldspar megacrysts, up to 1.5 cm long, vary from white to pale-pink where rocks are fresh, to deep-red in areas of alteration. Contacts with either the Cruachan facies or Quarry intrusion are not seen, although both are cut by thin sheets, or more commonly anastomosing veins, of this granite. In exposures on the flanks of Meall Cuanail, the granite contains large xenoliths of andesitic lava, similar to those of the Beinn a' Bhuridh screen, and of fine-grained acid (?rhyolitic) lava (Anderson, 1937).

Minor intrusions

The synplutonic intrusions of the Etive dyke-swarm consists mostly of steeply inclined NE-trending dykes, with a few shallow-dipping sheets (Figure 8.18). Branching and side-stepping along joint structures is a characteristic of many of these intrusions. The highest concen-

Figure 8.19 Aerial view of the Cruachan Reservoir GCR site, Etive pluton, looking WNW to Ben Cruachan. (Photo: BGS no. D 2571.)

tration of intrusions occurs in the country rocks and the swarm density decreases towards the centre of the pluton. Three distinct sub-suites are recognized as follows.

(a) Porphyritic andesites.
(b) Microdiorite, porphyritic micromonzodiorite/microgranodiorite (formerly 'porphyrites') and rare spessartite.
(c) Porphyritic microgranite (formerly 'quartz-porphyry') and aplitic microgranite (formerly 'felsite').

Members of sub-suite (a) occur only within the country rocks. These are dark grey-green, fine grained to aphanitic, and have been partially recrystallized by contact metamorphism. The more abundant microdiorite and microgranodioritic intrusions of sub-suite (b) may reach 15 and 35 m-thick respectively, but are mostly less than 6 m. The more basic intrusions are dark-green rocks, with phenocrysts of green or brown amphibole; the latter is commonly in association with augite, and plagioclase. The microgranodioritic rocks are a grey-buff colour, and are characterized by large oscillatory zoned crystals of plagioclase, 0.5–2 cm long. Plagioclase is the most abundant phenocryst in these rocks, with biotite predominant over amphibole. Within-dyke textural and compositional variations are common, often manifest as feldspathic net-veining.

On the basis of intrusive relationships the dyke swarm is further divisible into those that:

1. pre-date the Quarry intrusion;
2. are cut by the Cruachan facies or veins of monzodiorite/granodiorite;
3. cross-cut the Cruachan facies but are cut by the Meall Odhar facies or veins of similar age;
4. post-date all the main facies of the Etive pluton within the site.

Intrusions of sub-suite (c) consistently post-date all rocks of the pluton and the dykes of intermediate composition. A good example of this relationship is seen in the access road to the dam (0828 2735). All members of the Etive dyke-swarm are cut by ESE-trending quartz-dolerite and camptonite dykes of late Carboniferous to Permian age.

Interpretation

The origin of the Beinn a' Bhuridh screen is equivocal, although $^{87}Sr/^{86}Sr$ isotope values lie within the range of the Lorn Plateau lavas. However, contact metamorphic alteration is extensive, as seen by a $\delta^{18}O$ value of 6.3 (Frost and O'Nions, 1985), thus negating any meaningful comparison with other plutonic rocks or with Siluro-Devonian lavas. The arcuate form of the screen is compatible with Anderson's (1937) interpretation as a drop-down block within a ring fracture. There is no evidence for post-pluton emplacement ring fracturing within the GCR site, although elsewhere Anderson (1937) describes fault crush along the contact of the Quarry intrusion. Similarly, the shape of the satellitic Quarry intrusion suggests the exploitation of a pre-existing fracture system as a magma conduit.

Anderson (1937), following Nockolds (1934), attributed the turbid patches that disrupt oscillatory zoning in plagioclase crystals in the Quarry intrusion to contact metamorphism. However, this 'patchy zoning' is common in the Cruachan facies rocks, and is a feature of many plutons worldwide (cf. Vance, 1965). The origin of this texture is attributable to feldspar dissolution as a consequence of crystal-melt disequilibria during such processes as magma mixing (Wark and Watson, 1993). A pre-full crystallization texture is present in both the Quarry intrusion and the Cruachan facies. The absence of plastic strain fabrics and evidence of high temperature recrystallization, e.g. biotite overgrowth, argues against the dioritic Quarry intrusion being fully crystalline prior to pluton emplacement.

The multistage and multiple pulse emplacement history for the Etive pluton, described in the Bonawe to Cadderlie Burn GCR site report, is confirmed here. Both the Cruachan facies and the Quarry intrusion are cut by a large flat lying intrusion of the Meall Odhar facies at the highest preserved level within the pluton. Some members of the synplutonic dyke-swarm post-date all plutonic rocks within the GCR site. This points to the continued availability of Cruachan facies-type magmas after emplacement of Meall Odhar facies intrusions. This is demonstrated by the complex intrusive history of the Etive dyke-swarm, in which clearly defined sub-suites represent tapping of successive magma pulses during pluton emplacement. Cross-cutting relationships do not necessarily follow compositional maturity (i.e. acid cutting basic), but are time dependent, i.e. an acid intrusion of an earlier sub-suite will be cut by a basic component of a later sub-suite. The exception lies with the quartz-phyric and aplitic microgranites. These compositionally distinct intrusions post-date all basic to intermediate members of the swarm, and are likely to be penecontemporaneous with the Starav facies (not represented within this GCR site).

Conclusions

The Cruachan Reservoir GCR site is of national importance as a representative of the Etive pluton, in particular the satellitic Quarry intrusion, which is separated from the main pluton by a screen of andesitic lavas. The pluton is of major importance for its contribution to the understanding of multiple pulse emplacement mechanisms in the Caledonian plutonic suites. Of particular interest here are the numerous sub-suites of minor intrusions. Their emplacement relationships to facies within the Etive pluton, provide an unrivalled example of near-contemporaneous dyke intrusion into large bodies of magma that were still cooling. The high-level emplacement of the pluton is indicated by the presence of down-faulted volcanic rocks bound by a ring fracture. The arcuate form of the Quarry intrusion suggests exploitation of this fracture by the dioritic precursor magmas. Subsequent emplacement of the main body of the Etive pluton induced widespread baking and alteration of rocks within the envelope. Evidence for recrystallization of rocks within the satellite Quarry intrusion is, however, equivocal.

RED CRAIG (NO 293 758)

S. Robertson

Introduction

Red Craig lies at the eastern margin of the Glen Doll pluton, a member of the South of Scotland Suite of late Caledonian intrusions. The pluton has long been recognized as providing well-exposed and easily accessible evidence of the interaction between component magmas of a basic to intermediate intrusion (Barrow and Cunningham-Craig, 1912). The Red Craig area exhibits transitions from quartz-diorite through quartz-monzodiorite to granite. The igneous rocks are predominantly xenolithic and provide excellent examples of the interaction between the intermediate part of the pluton and the host Dalradian metasedimentary rocks.

The Glen Doll pluton occupies approximately 12 km^2 astride the Glen Doll Fault in the upper part of Glen Clova. The pluton is dominated by intermediate rocks of dioritic to tonalitic composition, although with a significant component of gabbro (Jarvis, 1987; Mahmood, 1986). Local olivine-pyroxenite (Mahmood, 1986) was previously referred to as serpentinite or picrite (Barrow and Cunningham-Craig, 1912). Barrow and Cunningham-Craig originally described a 'narrow fringe of encircling granite'; Jarvis, however, only recognized a marginal facies of medium-grained xenolithic granite along much of the southern and eastern part of the pluton.

The pluton was emplaced into dominantly semipelitic metasedimentary rocks assigned to the Argyll and Southern Highland groups of the Dalradian Supergroup (Figure 8.20). Little has been reported on the contact metamorphic effects of the intrusion, although Barrow and Cunningham-Craig recognized a zone of alteration at least 70 m-wide at the eastern margin but failed to detect any mineralogical alteration of the regional sillimanite zone rocks under the microscope.

Description

The GCR site at Red Craig provides a section through the eastern part of the Glen Doll pluton. Medium- to coarse-grained diorite and quartz-diorite, some of which is xenolithic, is typical of a large part of the pluton and passes east into a heterogeneous marginal zone of xenolithic quartz-diorite with areas of quartz-monzodiorite, granodiorite and granite. Xenoliths are mostly of high-grade hornfelsed semipelite, some of which show evidence of partial melting and assimilation into the diorite. Appinitic meladiorites are developed locally as are sheets and dykes of fine-grained felsite and quartz-feldspar porphyry.

Diorites and quartz-diorites are well exposed in a small roadside quarry near Braedownie (2882 7572) and on hillslope exposures to the NE on Dùn Mòr (290 759). Farther north there are numerous exposures although access is more difficult because of forestry plantations. The diorite on the south slopes of Dùn Mòr is cut by both granite veins and felsite sheets. The granite veins are typically only 5 cm thick, sinuous and generally steeply inclined, whereas the felsites are vertical and up to 1 m thick. Both have sharp margins with the host diorite. East of Dùn Mòr, an appinitic meladiorite contains large (4 mm) euhedral hornblende megacrysts within a finer-grained quartz-diorite or quartz-monzodiorite groundmass. The contact relationships of this unit cannot be seen on the steep and loose slopes. Appinitic rocks also occur farther north towards the Cald Burn (295 770). Xenoliths of hornfelsed semipelite occur quite widely within the diorite although many are only a few centimetres long. However, a xenolith (at 294 766) is at least 100 m long.

The diorites are separated from the host Dalradian rocks to the east by a 500 m-wide heterogenous zone of intermediate to acid igneous

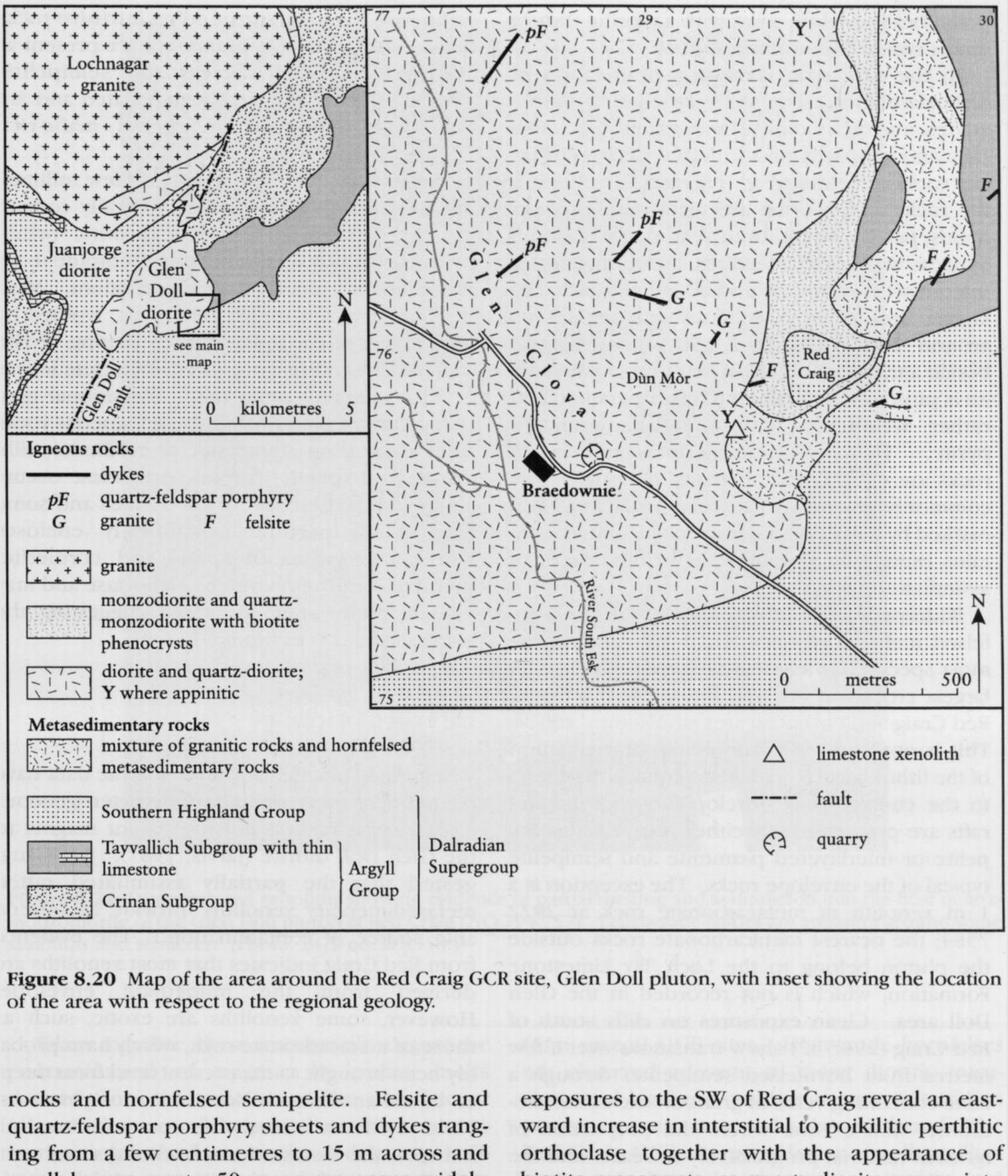


Figure 8.20 Map of the area around the Red Craig GCR site, Glen Doll pluton, with inset showing the location of the area with respect to the regional geology.

rocks and hornfelsed semipelite. Felsite and quartz-feldspar porphyry sheets and dykes ranging from a few centimetres to 15 m across and small bosses up to 50 m across occur widely. Within this zone, lithology, texture and grain size vary over short distances. Grey fine-grained diorite is net-veined by, and occurs as xenoliths within, medium-grained quartz-monzodiorite on the crags SW of Red Craig (2941 7558). Textural observations indicate that the fine-grained rocks were incorporated within and veined by the medium-grained rocks before crystallization was complete. Both are cut by veins and sheets of pink leucocratic granite up to 3 m thick. Craggy exposures to the SW of Red Craig reveal an eastward increase in interstitial to poikilitic perthitic orthoclase together with the appearance of biotite megacrysts, as quartz-diorite passes into quartz-monzodiorite. The quartz-monzodiorite forms a near continuous outcrop (Figure 8.20) and is typically grey and medium grained with biotite megacrysts up to 5 mm across comprising approximately 5% of the rock. In thin section, the quartz-monzodiorites show evidence of the addition of a potassic component to a parent diorite or quartz-diorite magma. The biotite megacrysts, together with perthitic orthoclase megacrysts that comprise up to 30% of the rock, poikilitically enclose areas with a dioritic texture that is typical of diorites to the west.

To the east, with increasing proportions of orthoclase and quartz, the quartz-monzodiorite grades into granodiorite and granite in which rafts and xenoliths of hornfelsed metasedimentary rocks are widespread (Figure 8.21). Many of the rocks in this zone are texturally heterogeneous; patches with dioritic texture are enclosed by areas with granitic features, including graphic intergrowths of quartz and alkali feldspar. The largest area of homogeneous granite is seen around 2967 7620, in a 150 m-long section beside a track, 200 m NE of Red Craig. The granite is pink to red, medium to coarse grained and rather weathered with some disseminated pyrite. The neighbouring metasedimentary rocks are cut by granite sheets, although more commonly granite contacts are gradational and marked by transition zones in which granite contains numerous xenoliths in various stages of assimilation.

Widespread xenoliths and larger rafts of hornfelsed metasedimentary rock form some of the most spectacular features of the GCR site. The largest crops out on, and immediately west of, Red Craig and covers an area of 250 m × 200 m. This is not a roof pendant since the inclination of the lithological layering is rotated with respect to the country rock envelope. Xenoliths and rafts are predominantly either hornfelsed semipelite or interlayered psammite and semipelite typical of the envelope rocks. The exception is a 1 m xenolith of metacarbonate rock at 2922 7584; the nearest metacarbonate rocks outside the pluton belong to the Loch Tay Limestone Formation, which is not recorded in the Glen Doll area. Clean exposures on cliffs south of Red Craig (294 757) show transitions over a few metres from hornfelsed semipelite, through a zone containing veins of granodiorite or monzodiorite, into a zone where the proportion of igneous material progressively increases and the semipelite becomes detached and re-orientated. This is followed by quartz-monzodiorite or granodiorite with heterogeneous grain size and texture, choked with randomly orientated xenoliths and schlieren in various stages of assimilation, ranging from a few millimetres to many centimetres long. Some xenoliths contain lenses or veins of pink granite, commonly less than 1 cm thick, which both permeate and cross-cut the lithological layering. They are mantled by biotite and encircled by leucocratic haloes with more orthoclase than the surrounding intrusive rocks (Figure 8.21). Locally, psammites are present as discrete xenoliths whereas the semipelitic interbeds have been largely assimilated and are preserved only as dismembered mafic-rich schlieren.

Semipelitic xenoliths, whether a few millimetres or tens of metres across, typically contain the assemblage: cordierite + perthitic orthoclase + plagioclase + sillimanite + biotite + qu artz + minor spinel + minor corundum. Most are compact dark bluish-grey rocks, typified by rusty and in places gossanous weathering. Pyrite is abundant and occurs either in discrete lenses or with quartz segregations. Transitional contacts between the semipelites and igneous rocks show decreasing abundance of cordierite, sillimanite and spinel. Perthitic orthoclase occurs along with plagioclase, larger biotites and some quartz; the perthite poikilitically encloses biotite, aggregates of spinel and cordierite. Biotite is locally embayed by orthoclase and may include pinite after cordierite, suggesting the local breakdown of biotite.

Interpretation

Whole-rock geochemical and isotopic data have been interpreted as indicating heterogeneous crustal contamination of the parent magma to the Glen Doll diorite (Jarvis, 1987). Jarvis suggested that the partially assimilated rafted metasedimentary xenoliths 'provide an observable source of contamination'. The evidence from Red Craig indicates that most xenoliths are derived from the immediate envelope. However, some xenoliths are exotic, such as those of metacarbonate rock, which have probably been brought to the present level from deeper in the intrusion. None are roof pendants. Field evidence clearly demonstrates a link between the distribution of xenoliths and contamination of the quartz-diorite melt by granitic melt. The xenolith-rich zone also coincides with a heterogeneous, hybrid igneous assemblage, ranging from quartz-monzodiorite to granite and characterized by the presence of orthoclase and biotite megacrysts. On a small-scale there is a close association between the abundance of orthoclase within the igneous rocks and proximity to xenoliths. The occurrence of interfingering granitic segregations with graphic textures in the xenoliths indicates partial melting.

Figure 8.21 Disaggregated xenoliths showing evidence of partial melting and assimilation into the host quartz-monzodiorite of the Glen Doll pluton at Red Craig (NO 294 757). Leucocratic haloes are apparent around some xenoliths and schlieren. (Photo: BGS no. D 4550.)

Taken together, these features all suggest the contamination of magmas by partial melts derived from the xenoliths. The poikilitic or interstitial nature of the partial melt component, comprising orthoclase, biotite and quartz, indicates that it was introduced into the diorites after they had partly solidified. Minor granite veins may also be derived from melting of xenoliths although their sharper margins may indicate derivation from deeper within the pluton.

Conclusions

The assimilation of country rocks, resulting in contaminated xenolithic zones, is common in the Caledonian intrusive suites and is described from several GCR sites. High-grade hornfelses are observed adjacent to many dioritic intrusions and localized melting of country rocks to produce granitic magma has been inferred. The Red Craig GCR site provides an excellent illustration of all of these processes *in situ* and hence is a site of national and possibly international importance. Here a dioritic magma has been contaminated both with xenoliths and with a granite melt that was derived locally from within the xenoliths. The largely semipelitic xenoliths range from a few millimetres to more than 200 m across. They preserve high-grade contact metamorphic mineral assemblages and some have granitic segregations indicating partial melting. Many have transitional contacts with the host dioritic rocks where their marginal parts have been spalled off and assimilated by the magma.

FOREST LODGE (NN 933 741)

D. Stephenson

Introduction

In the second half of the eighteenth century the controversy regarding the origin of rocks which we now regard as 'igneous' was at its height. On the one side were the *Neptunists*, inspired by the teaching of Abraham Werner in Saxony, who believed that rocks such as basalt and granite were 'sedimentary', having crystallized from a supposed primeval ocean, as rock-salt does from today's oceanic water. Granites were considered to have crystallized first, to form a thick layer around the Earth's 'nucleus'. The granites were overlain by other layers of crystalline rock, those that we now know as 'metamorphic', followed by layers of sedimentary rock formed as a result of erosion of the 'Primitive' crystalline rocks and subsequent deposition. Rocks resulting from observed volcanic eruptions were attributed to the local action of 'subterraneous fires' (generally thought to be due to the burning of coal seams), but these, it was believed, could only consolidate as a glass.

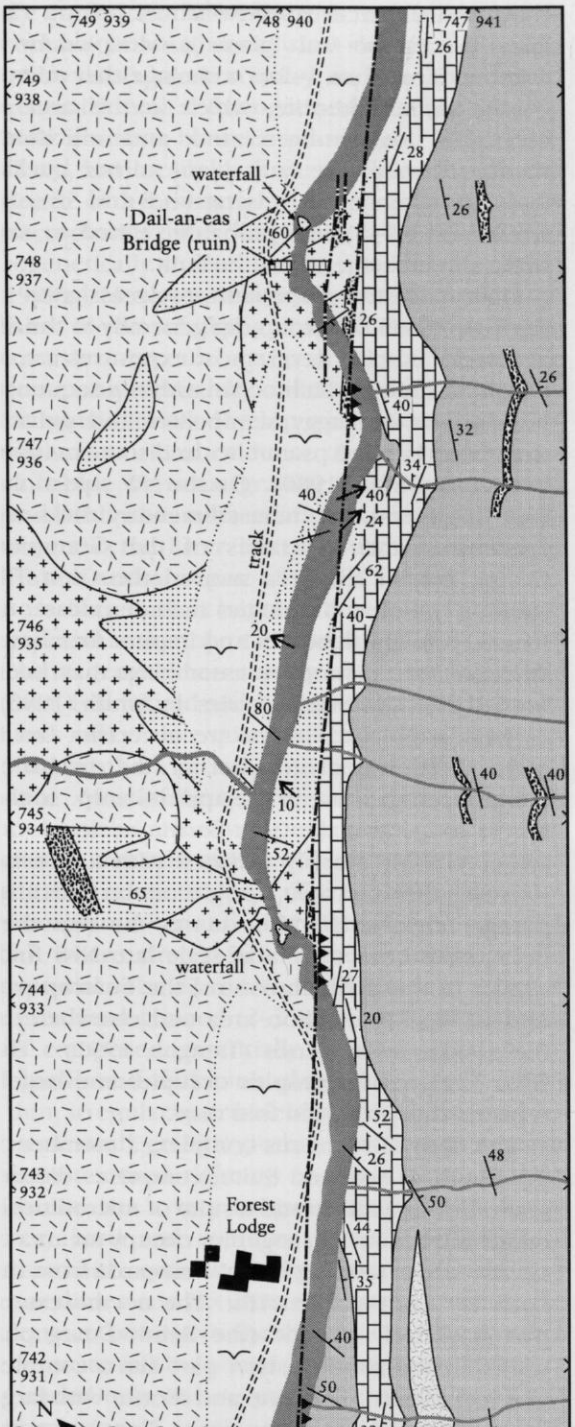
By the 1760s prehistoric volcanic features had been recognized, in particular in the Auvergne region of France, where flows of crystalline basalt had been traced back into undisputed volcanic craters. The *Vulcanists* had made their point and gradually, over the next fifty years, most Neptunists came to accept the magmatic origin of basalt. The origin of granite was more difficult to prove since, by its very nature according to any of the theories of the day, it could not be observed forming *in situ*. It was James Hutton (1726–1797), a prominent member of the Edinburgh scientific community, who was to lead the *Plutonists* in establishing that granite crystallized from a molten fluid and not from an aqueous solution.

In his 'Theory of the Earth', delivered in two lectures to the Royal Society of Edinburgh in the Spring of 1785 (Hutton, 1788), he argued that the relative insolubility in water of quartz and other component minerals of granite, precluded the Neptunist theory. He recognized the significance of the intergrowth texture between quartz and feldspar in a sample of coarse-grained graphic granite (Hutton, 1788, plate II) and concluded that granite might have 'risen in a fused condition from subterranean regions' and that the country rock should therefore be broken, distorted and veined.

In the late summer of 1785, Hutton embarked upon the first of several excursions to find field evidence in support of his philosophical theories; these must have been among the first ever geological field trips. From the examination of debris washed down by rivers in the Highlands, he had already concluded that a major junction existed somewhere in the region of Glen Tilt, between a largely granitic terrain to the north and *'alpine schistus'* to the south. He stayed at Forest Lodge, where he soon found the evidence that he was seeking, particularly in those exposures in the bed of the River Tilt, less than 1 km from the lodge, which now constitute the GCR site. In Hutton's words, 'the granite is here found breaking and displacing the strata in every conceivable manner, including the fragments of the broken strata, and interjected in every possible direction among the strata which appear'. He also inferred from the highly crystalline nature of the country rocks that they had been subjected to intense heat and that the granite was responsible; hence the granite must have been injected as a very hot liquid, i.e. a magma.

Over the next three years Hutton was to find and document further examples of granite veining, particularly in Galloway and on the Isle of Arran, and a brief account of the field evidence was included in a discussion of the origin of granite (Hutton, 1794). The Glen Tilt sites were revisited by several of Hutton's contemporaries (Playfair, 1802; Seymour, 1815; MacCulloch, 1816), but his own detailed descriptions were not published until 100 years after his death in volume 3 of 'Theory of the Earth', edited by Archibald Geikie (Hutton, 1899). By this time the magmatic origin of granite had, for the time being at least, become universally accepted and the Neptunist theory had lapsed into historical significance. In 1968 a collection of drawings came to light, many of which were clearly intended to accompany volume 3 of 'Theory of the Earth', but were 'lost' prior to its publication (Craig *et al.*, 1978). Several depict the Glen Tilt exposures and one is reproduced here (Figure 8.24).

The exposures described by Hutton occur on



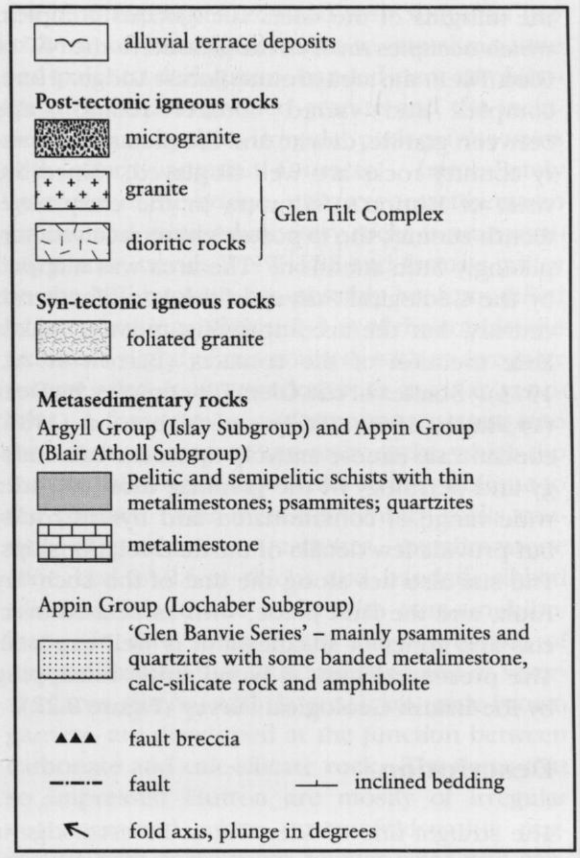


Figure 8.22 Map of the Forest Lodge GCR site, Glen Tilt igneous complex, based on unpublished British Geological Survey maps by D. Stephenson and B. Beddoe-Stephens. Note: Much of the area to the NW of the River Tilt is covered by head and scree deposits. Boundaries in this area are highly conjectural and the area shown as 'dioritic rocks' probably includes areas of granite and metasedimentary rocks.

the margins of the Glen Tilt igneous complex, which occupies most of the ground to the NW of Glen Tilt in the area around Forest Lodge. Here, complex and varied contact relationships between granite, diorite and the metasedimentary country rocks are well displayed. Since the visits of Hutton's followers in the early nineteenth century, the exposures have received surprisingly little attention. The area was mapped by the Geological Survey in the late nineteenth century, but the accompanying memoir makes little mention of the contacts (Barrow *et al.*, 1913). Studies of the Glen Tilt complex by Deer (1938a, b, 1950, 1953) and Mahmood (1986) concentrate almost entirely upon the mineralogy and petrology of the granites, diorites and a wide range of contaminated and hybrid rocks, but provide few details of the field relationships. The site also lies along the line of the Loch Tay Fault, and the fault plane, with associated breccias and zones of silicification, is well exposed. The present account is based upon remapping by the British Geological Survey (Figure 8.22).

Description

The straight line of Glen Tilt at Forest Lodge is controlled by the Loch Tay Fault, one of the most important NE–SW-trending late Caledonian faults in the Grampian Highlands. Farther to the SW around Loch Tay, the fault has a net sinistral strike-slip movement of 7 km and a downthrow of at least 0.5 km to the SE (Treagus, 1991). In Glen Tilt the fault juxtaposes Grampian Group (and possibly lowest Appin Group) strata, cut by rocks of the Glen Tilt igneous complex, to the NW against upper Appin Group strata to the SE. There are no major intrusions and no widespread contact metamorphism to the SE of the fault. This would appear to be consistent with a significant downthrow to the SE, although there are no indications of the extent of strike-slip displacement in this area.

Where seen, the fault plane is near vertical and sharply defined, as below the waterfall at 935 743. It is commonly marked by zones of brecciation and silicification, such as below the waterfall at 938 746 and in the river due south of the lodge (932 740). The zone of brecciation is never very wide, considering the magnitude of the fault, and rarely extends for more than about 10 m on either side of the fault plane. Silicification can extend slightly farther and is particularly noticeable in limestone beds which take on a distinctive yellow-brown colour. In many places the fault plane is occupied by a dyke, no more than 1–2 m wide, of either microgranite or microdiorite, which in this area is invariably highly brecciated and silicified. Within 20 m of the fault plane minor buckle folds plunging generally between E and SE (e.g. around 937 745) are probably related to the strike-slip movements on the fault.

On the SE side of the fault, rocks assigned to the Blair Atholl Subgroup dip generally to the SE at 25–45°. At river level, most exposures are of metalimestones, which occur within a sequence of schistose to flaggy semipelites and pelites, with flaggy banded psammites and some massive quartzites (Smith, 1980). On the NW side of the fault in general, the metasedimentary rocks are psammites and quartzites of the Grampian Group, but in the area around the Glen Tilt igneous complex, lithologies include calcareous schists, para-amphibolites and impure metalimestones. This distinctive assemblage has been termed the Glen Banvie 'series' by Smith (1980); its stratigraphical affinities are uncertain, but it may be equivalent to part of the Lochaber Subgroup at the base of the Appin Group. In the Forest Lodge area the Glen Banvie 'series' rocks are commonly steeply inclined with a general NW–SE strike and tight upright minor folds that plunge north at 10–20°. It may be that they occupy the core of a large-scale late N–S fold, similar to those which control the outcrop pattern in the Schiehallion area and elsewhere in the Southern Highlands (Treagus, 1991). The Glen Tilt igneous complex occupies and largely replaces this proposed fold core.

The Glen Tilt igneous complex, a member of the South of Scotland Suite, comprises diorite, granodiorite, granite and a suite of microdioritic minor intrusions that together occupy an area of 12 × 6 km, extending north-westwards from the Loch Tay Fault in Glen Tilt. The north-western part is entirely granitic (the Beinn Dearg pluton), but the south-eastern part has a complex outcrop pattern of granite and diorite with large areas of metasedimentary rock. Exposures are discontinuous, especially on the lower valley sides around Forest Lodge, where scree and other superficial deposits cover much of the outcrop. Consequently, the form of the intrusions is difficult to determine; dioritic rocks form most of the area to the NE of the lodge, with many small outcrops of biotite granite around the lodge itself. Intrusive relationships, where seen, are equivocal. The granite is not chilled at any contacts, although locally it is slightly reduced in grain size against country rocks. The diorite generally has a finer-grained marginal facies. Most contacts between granite and diorite are sharp, but locally they are gradational with evidence of hybridization. The granite is cut by microdiorite dykes that seem to be related petrogenetically to the diorites (Beddoe-Stephens, 1999). However, marginal granite locally contains blocks of fine-grained basic rock in an intrusion breccia; marginal dioritic rocks are commonly veined by aplitic granite; and some marginal diorites develop small feldspar porphyroblasts. Critical evidence of the intrusive relationships between granitic and dioritic rocks and with the metasedimentary country rocks occurs in the River Tilt exposures, examined by Hutton and now part of the GCR site.

A sharp contact between diorite and granite is exposed at the top of a waterfall (935 743). The biotite granite, here mostly on the SE side of the river, is brick red and equigranular with conspicuous milky white quartz up to 5 mm in diameter that weathers proud to give a nodular appearance. Most of the outcrop close to the contact is an irregular mix of veins of granite, granodiorite, diorite and vein quartz with no consistent cross-cutting relationships. The veining continues into psammites and quartzites above the waterfall where almost 50% of the exposure is vein material. The diorite on the NW side of the river is medium grained (2–3 mm), equigranular and is composed essentially of dark-green hornblende and dark-pink plagioclase. It is cut by thin, irregular quartzofeldspathic veins and contains small granitic pods. The diorite remains even textured right up to the contact, but the granite has a very irregular texture and is also very hard and splintery. Small inclusions of psammite, quartzite, calc-silicate rock and grey metalimestone occur in the granite close to the contact, but not in the diorite. An island within the waterfall is formed by a larger inclusion of banded quartzite or psammite cut by pods and thin veins of granite, and the NW edge of this inclusion is marked by an intrusion breccia of quartzite/psammite and some amphibolite in a dioritic matrix.

The waterfall beneath the ruined abutments of Dail-an-eas Bridge (939 747) (Figure 8.23) was the main focus of Hutton's observations and figures in several of his drawings (Figure 8.24). The abutments rest upon a coarse-grained brick-red biotite granite, crowded with xenoliths (up to 2 m), of psammite, quartzite, metalimestone and pale- to dark-green, banded para-amphibolite. The coarse-grained granite and the inclusions are cut by thin, irregular pink granite veins with sharp, angular contacts. Immediately upstream of the bridge, a sharp contact between granite and metasedimentary rocks is near vertical, planar, trends WNW–ESE and forms a gulley on the NW bank; it has possibly been modified by later faulting. Within 2–3 m of the contact the granite is slightly finer grained, with an irregular texture, and it is crowded with angular xenoliths. A few veins of red granite penetrate into the adjoining metasedimentary rocks, which dip steeply southwards and strike slightly oblique to the contact. The metasedimentary rocks consists of psammites, quartzites, metalimestone (one bed is 2.5 m thick) and banded, ribbed siliceous calc-silicate rocks with para-amphibolites. In thin section they show evidence of recrystallization due to hornfelsing and in several places skarns, with large (1 cm) pale-brown garnets, are developed at the junction between carbonate and calc-silicate rock. The veins that so impressed Hutton are mostly of irregular coarse-grained white quartzofeldspathic pegmatite, with some more regular veins and concordant sheets of white to grey microgranite or microgranodiorite. There are a few irregular veins of pink granite but, except for those at the contact (see above), these do not resemble the main granite body.

Interpretation

Although Hutton had correctly deduced that a junction between granite and 'schistus' would be found in Glen Tilt, he was unaware of the presence and significance of the Loch Tay Fault. So it was fortuitous that he found his evidence so easily; he may well have met with only a faulted contact with no veins, xenoliths or other evidence to indicate an intrusive relationship. The contacts of the intrusive complex with large masses of metasedimentary rock are well exposed only in the valley bottom, where the River Tilt departs from the line of the fault plane, albeit by less than 50 m, in places like Dail-an-eas. Fortunately, the zone of brecciation and alteration associated with the fault is too narrow to have affected these outcrops and obliterate the detail.

The presence of large outcrops of metasedi-

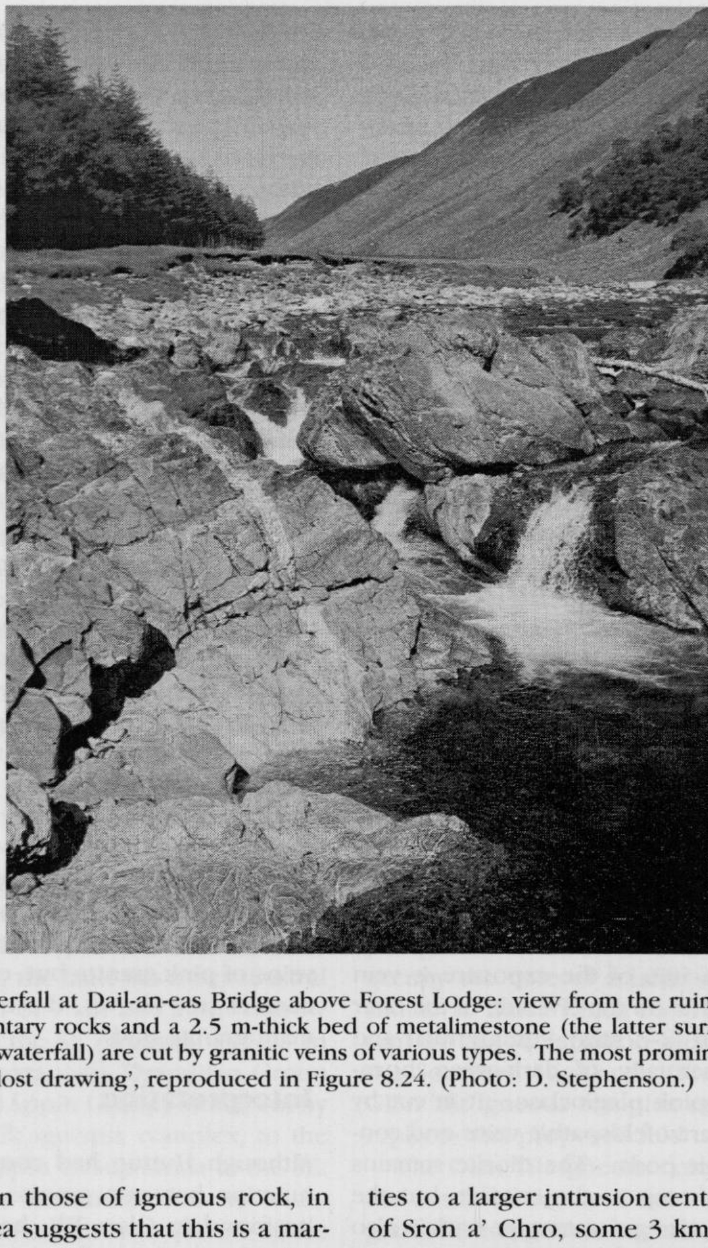


Figure 8.23 The waterfall at Dail-an-eas Bridge above Forest Lodge: view from the ruined bridge abutment. Siliceous metasedimentary rocks and a 2.5 m-thick bed of metalimestone (the latter surrounded by and tunnelled through by the waterfall) are cut by granitic veins of various types. The most prominent vein is also clearly visible in Hutton's 'lost drawing', reproduced in Figure 8.24. (Photo: D. Stephenson.)

mentary rock, within those of igneous rock, in the Forest Lodge area suggests that this is a marginal zone of the intrusive complex. Unfortunately the exposures are too discontinuous to identify this as either a roof zone with pendants, a lateral margin with screens, or an area of in-situ country rock heavily impregnated with veins and irregular apophyses from the main intrusions. The consistent NW–SE strike of the bedding and shallow northerly plunge of fold axes in most of the outcrops does however suggest that re-orientation as a result of the intrusions has been minimal. The form of the main intrusions is likewise impossible to determine. Many of the granite outcrops seem to be relatively small, isolated bodies, but they are all coarse grained and have petrographical similarities to a larger intrusion centred upon the ridge of Sron a' Chro, some 3 km to the west. The diorite is more widespread and continuous, dominating the higher, craggy slopes of Glen Tilt to the NE; it could be a highly irregular, steep-sided intrusion, but the outcrop pattern could be interpreted as a thick low-angled sheet with the Forest Lodge outcrops close to the lower margin.

Intrusive relationships between the granite and diorite are ambiguous. Earlier workers (Deer, 1938b; Mahmood, 1986) regarded the diorites as earlier. This is supported by the presence of granitic veins and feldspar porphyroblasts in the diorite. However, recent field and petrological studies (Beddoe-Stephens., 1999) suggest that the Sron a' Chro and related granite

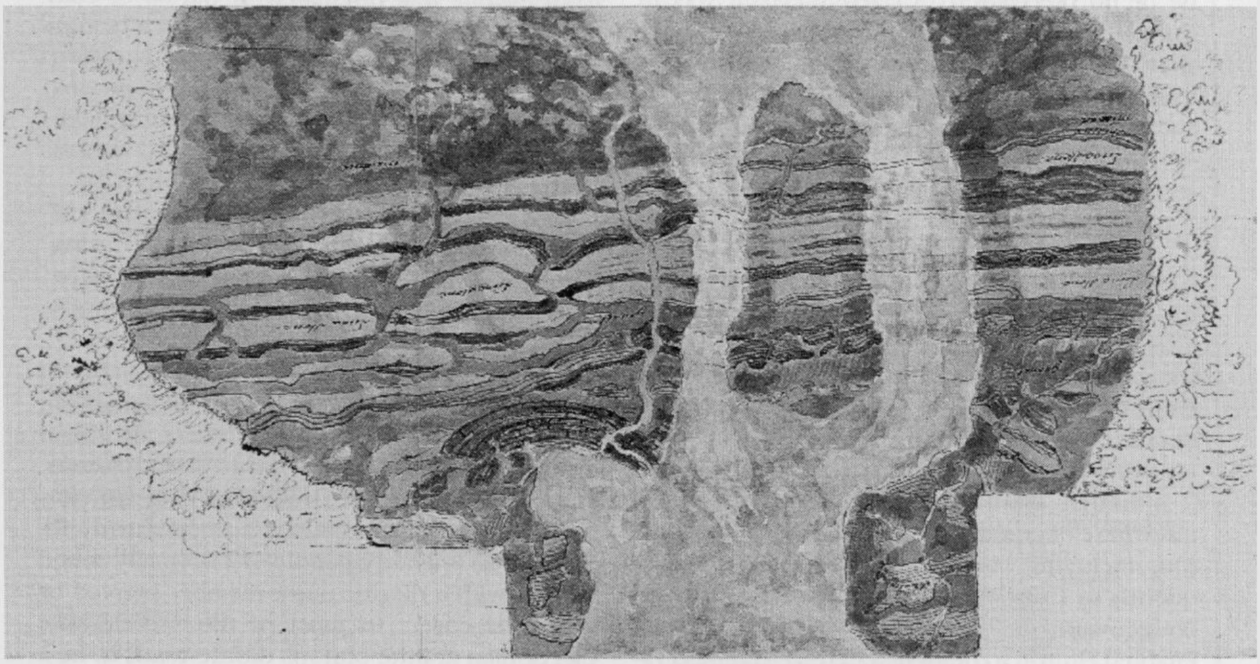


Figure 8.24 Plan of exposures in the River Tilt on the upstream side of Dail-an-eas Bridge, drawn by John Clerk of Eldin during Hutton's visit in 1785 and published as one of Hutton's 'lost drawings' by Craig *et al.* (1978). The outline is inaccurate and the detail is somewhat exaggerrated and stylized, but it illustrates well the features that Hutton observed; in particular the 'granite', 'limestone', 'schistus' and 'mixed rocks' are clearly labelled on the original. Note that the drawing is reproduced upside down to facilitate comparison with the photograph of Figure 8.23; the bridge abutments are indicated by the blank rectangles (bottom right and bottom left). Reproduced by permission of Sir John Clerk.

bodies in the Forest Lodge area were the earliest phase of the complex and that, during subsequent intrusion of the diorite, melting, hybridization and remobilization occurred, with back-veining of aplitic and pegmatitic veins into the still hot diorite. During crystallization of the diorite, slightly fractionated melts were expelled to form the microdiorite dykes which cut the Sron a' Chro granites.

Within the GCR site, the overall impression is that the diorite cuts the granite. Whereas the granite is commonly crowded with metasedimentary xenoliths, none of diorite are recorded. The diorite has far fewer metasedimentary xenoliths, giving the impression of a later event and the rounded pods of granite that have been recorded could be partly digested xenoliths. The granite is slightly finer grained against the metasedimentary rocks, but not against the diorite. It develops a highly irregular texture against both, but is hard and splintery against the diorite suggesting secondary silicification during recrystallization. More importantly, whereas thin sections of the diorite show primary crystallization textures, those of the granite show evidence of strain-related recrystallization, implying thermal and deformational events associated with the diorite emplacement.

Relationships of the Loch Tay Fault to the intrusions are interesting. Treagus (1991) considers that the major NE–SW faults of the Grampian Highlands were initiated as dextral shears during a late phase of N–S-trending folding, which pre-dated the major intrusions. The Glen Tilt complex does seem to be located in the core of a major N–S late fold and an early shear or fracture could possibly have controlled the location of the SE margin or even have acted as a magma conduit. Clearly the major movements on the fault post-date the main intrusions of the complex, which are truncated and which do not appear on the downthrown SE side. Neither is there any major aureole development on the SE side. However, throughout most of its length in upper Glen Tilt, the fault plane contains minor intrusions of microgranitic and microdioritic rocks; most are highly brecciated with much secondary silicification, but others have suffered little or no brecciation. Clearly the fault was in existence soon after the emplacement of the Glen Tilt Complex, to control the site of minor intrusions. Some of these were then affected by subsequent brittle movement, to complete a long and complex cycle of inter-related faulting and intrusion in late Caledonian time.

Conclusions

This site is of international importance on historical grounds. It was here in 1785 that James Hutton first found and documented field evidence to support his theory that granite was intruded into country rocks in a hot, fluid state.

Although there are much clearer examples elsewhere of granite veins emanating from a pluton, including some that were visited subsequently by Hutton, the exposures around Forest Lodge were the first to be evaluated. They enabled Hutton to demonstrate that granite crystallized from 'matter made fluid by heat', i.e. magma; that this matter was able to flow within the Earth's crust, veining, disrupting and recrystallizing pre-existing rocks; and that consequently granite is not universally the earliest formed rock. This effectively ended the Neptunist arguments of Werner and his disciples and for well over a hundred years was accepted as a satisfactory explanation for the origin of all granites.

It was not until the 20th century that people began to address the problem of where and how granitic magma might be generated. Once again this led to a division into two camps, with the essentially Huttonian 'magmatists' opposed by 'transformationists' who believed that granite was generated *in situ* from pre-existing rocks, by fluid or gaseous 'fronts' which modified the composition, mineralogy and texture of the rock without generating a melt; the process of 'granitization'. This time, however, it eventually became accepted that both arguments have their merits and that granites have formed in many different ways; in the words of H. H. Read (1957), 'there are granites and granites'. Mechanisms such as broad-scale, in-situ, solid state diffusion as a product of ultrametamorphism and the precipitation of granitic pegmatites from silicic, hydrous fluids are now well documented, and fractional crystallization of a more basic magma can result in a granitic residual melt. But by far the greatest volumes of granite are now considered to have crystallized from magma that originated by partial or complete melting of crustal material; a true vindication of the Huttonian theory.

FUNTULLICH (NN 750 265)

W. E. Stephens

Introduction

The Comrie pluton (Figure 8.25) is a member of the South of Scotland Suite. It is somewhat unusual among the Scottish late Caledonian intrusions in its isolation from other plutons, and by the fact that the strike of its long axis runs counter to the main NE–SW Caledonian trend. The pluton is a fine example of a normally zoned pluton, with a dioritic outer member pierced by a granitic core. In most of the Scottish late Caledonian granite plutons diorite tends to be a minor component whereas more acid rocks are more abundant. The Comrie pluton is unusual in that diorite is the dominant lithology (see also the Craig More GCR site report). There is considerable heterogeneity among the diorites, and a sharp contact can be observed between the granitic rocks and the outer dioritic envelope. This is important, as in similar plutons elsewhere in Scotland the contacts are not usually exposed and gradational changes are often described. In this case the sharp contact and xenolithic inclusions clearly demonstrate the importance of multiple pulses in the construction of some of the late Caledonian plutons. An age of 408 ± 5 Ma has been obtained using Rb-Sr on whole rock-mineral pairs (Turnell, 1985).

Many of the late Caledonian 'granites' of Scotland are diorite–granodiorite–granite complexes in which the central and youngest magmatic member is located in the centre of the pluton. It has been long debated whether this disposition is the product of in-situ fractional crystallization, with early higher temperature minerals forming first near the cooler walls, or whether such plutons represent separate pulses of magma intruded either directly from the source of melting, or from an intermediate magma chamber. Many such plutons have been described from around the world and the form is known as normal zoning. Just how such plutons are constructed is the subject of considerable debate (e.g. Paterson *et al.*, 1996; Petford, 1996), and the question of whether plutons are constructed from single or multiple magmatic pulses is important in understanding the mechanisms involved. The Comrie pluton is one of the few good examples of multiple pulses in the British Caledonian igneous province.

The Funtullich GCR site displays many of the key features of the Comrie pluton in one small area. The main interest of this site is igneous, with all principal members of the pluton exposed and showing internal contact relationships. In addition, the contact effects of the pluton on the more psammitic lithologies of the Ben Ledi Grit may be examined and contrasted with the effects on the Aberfoyle Slate, seen in the Craig More GCR site. For reasons of outcrop quality and accessibility this site is widely used for instructional purposes, and the site is included in the excursion guide of MacGregor (1996).

Description

Diorites form much of the outer part of the pluton (see the Craig More GCR site report) but the central area, forming the high ground SW of Carn Chois, is formed of pink microgranite. An extension of this microgranite cuts through the diorites in the Funtullich area, and dioritic xenoliths are abundant close to this internal contact. A sheet of similar microgranite occurs in contact with the Ben Ledi Grit.

The diorites around Funtullich farm (Figure 8.26) are compositionally and texturally highly variable. A dark fine-grained variety seen near the road comprises hornblende and biotite with slightly altered plagioclase and minor quartz. Biotite generally occurs with opaques or in clusters with hornblende. Farther to the east of the road the rock becomes coarser grained with large crystals of hornblende (sometimes obviously after pyroxene) and plates of biotite within a matrix of altered plagioclase. Other varieties of diorite contain fresh pyroxenes, commonly both ortho- and clinopyroxene. These rocks range from 53–60% SiO_2, and geochemical characteristics suggest that some may be mafic-rich cumulates. Compositional heterogeneity in the diorites extends them into the granodiorite field, and some more evolved types reach about 65% SiO_2.

Intruding these various diorites is a mass of pink medium-grained granite (microgranite) which is best displayed in the nearest crags to the ENE of Funtullich. At the western end of

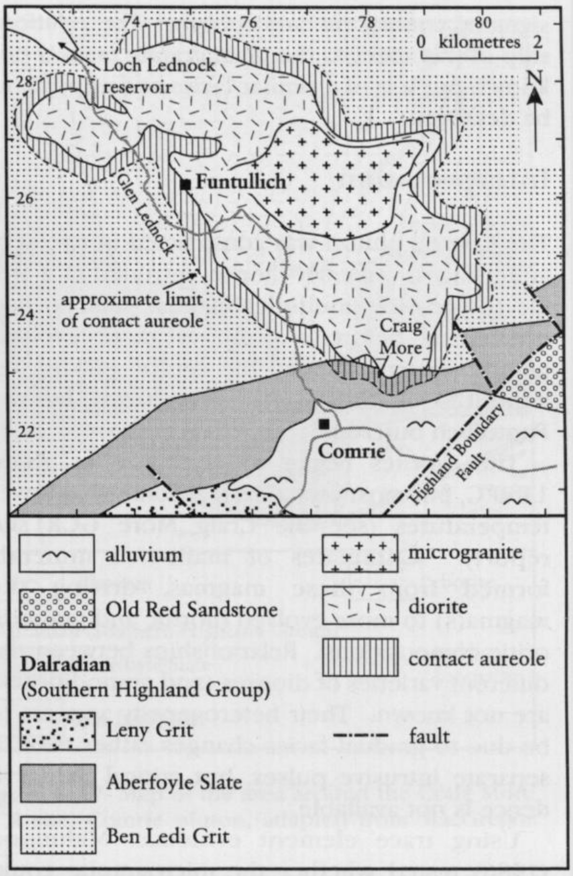


Figure 8.25 General location map of the Comrie pluton. Taken from a paper by Pattison and Tracy (1991), who drew it from data in Tilley (1924).

these crags is a coarse-grained diorite with pink aplitic veins, and a solitary tree marks the line of contact with the microgranite. Eastwards from this contact the microgranite contains abundant dark xenoliths, including some of dioritic composition. The mineralogy of the microgranite comprises principally plagioclase, orthoclase and quartz with biotite as the principal mafic mineral, together with aggregates of amphibole and biotite. This microgranite has an SiO_2 content of about 71% and it is depleted in most trace elements except Rb, relative to the outer diorites (Mahmood, 1986).

The outer contact of the pluton can be seen about 100 m NW of Funtullich, on the SW side of the road. Here a sheet of pink microgranite with prominent sub-horizontal joints is in contact with the Ben Ledi Grit. The contact can be located to within a metre or so, but here the psammitic rocks of the envelope show no obvious signs of contact metamorphism. The relationship of this sheet to the main granite mass is not known but it is of a similar facies and appears to be detached.

Interpretation

The Comrie pluton was constructed in two separate stages. An early diorite, intruded as a single (or possibly multiple) magma pulse(s) had crystallized before a pulse of more evolved granitic magma pierced the centre, picking up xenoliths of the diorite, as shown by the Funtullich outcrops.

The diorites began to crystallize at about 1100°C, but most crystallized at somewhat lower temperatures (see the Craig More GCR site report). Cumulates of mafic-rich minerals formed from these magmas, driving the magma(s) to more evolved dioritic and granodioritic compositions. Relationships between the different varieties of diorites (and granodiorites) are not known. Their heterogeneity appears to be due to gradual facies changes rather than to separate intrusive pulses, but critical field evidence is not available.

Using trace element evidence, Mahmood (1986) tested whether the microgranite could have been derived directly from the dioritic parental magma through fractional crystallization. The data show that this model is not tenable as no incompatible trace element (not even Rb) in the microgranite exceeds abundances found in the granodiorites. Hence, the central microgranite appears to have formed from the crystallization of a separate single pulse of magma.

Two samples from the diorites have yielded Sr isotope initial ratios of 0.7050 (Turnell, 1985). Such values can be interpreted as indicating a deep crust or upper mantle source. Whole rock-mineral separates on the same two diorite samples give concordant Rb-Sr ages of 408 Ma (Turnell, 1985), the probable minimum age of intrusion.

Conclusions

The Funtullich outcrops of the Comrie pluton afford an opportunity to view a wide range of rocks from diorite to granite in a small area, with an observable contact between a late granite and the host diorite, clearly establishing the age relationships. The outcrops display many of the essential field relationships that are required to understand the construction of zoned plutons, which commonly provide valuable information on the generation and evolution of deep crustal magmas.

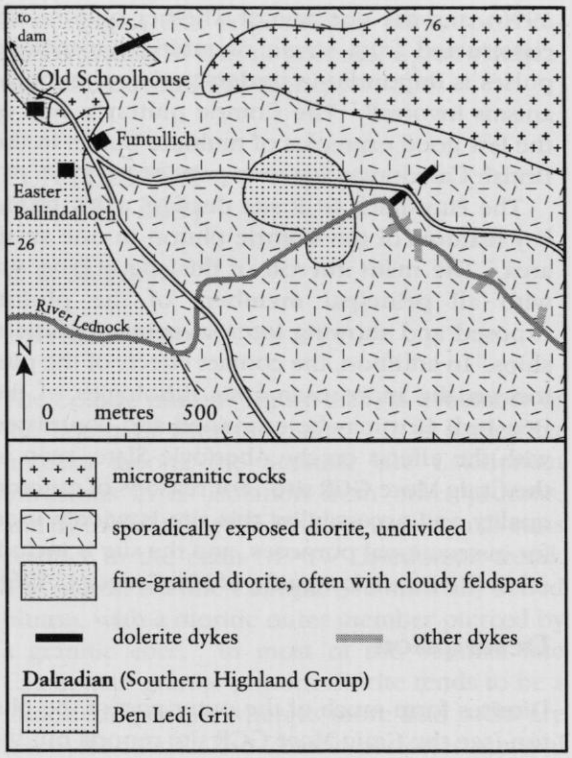


Figure 8.26 Map of the area around the Funtullich GCR site, Comrie pluton, adapted from MacGregor (1996).

CRAIG MORE (NN 787 227)

W. E. Stephens

Introduction

The Comrie pluton of Perthshire is best known for the classic study of a contact metamorphic aureole made by Tilley (1924), following Nichol (1863) who was the first to observe the hardening of the slates and attribute this to recrystallization close to the igneous contact. The intrusion of the pluton into Dalradian metasedimentary rocks with a variety of pelitic, semipelitic and psammitic lithologies and low regional metamorphic grade made it ideal for these pioneering studies. More recently the high-grade contact metamorphic rocks adjacent to the pluton have been studied in detail (Pattison and Harte, 1985) and a low-pressure environment of contact metamorphism has been established from the mineral assemblages. In a classification of contact metamorphic facies series (Pattison and Tracy, 1991), the aureole is cited as a type example of a particularly low-pressure facies that is notable for the prevalence of spinel and hypersthene and the absence of garnet in high-grade cordierite-bearing assemblages.

The Craig More GCR site has excellent exposures of pelitic rocks throughout the increasing contact metamorphic grade up to the contact with the diorite, and is included in the excursion guide by MacGregor (1996).

Description

The area between the Caravan Park at Old Lodge and the margin of the diorite just east of Craig More represents a complete section through the aureole (Figure 8.27). Here the country rocks are the Aberfoyle Slate of the Southern Highland Group of the Dalradian. The unaffected rocks near Old Lodge are greenish pelites said by Tilley (1924) to lie in the chlorite zone of regional metamorphism.

In a traverse from outside the aureole up to the igneous contact the following sequence of changes can be observed. About 400 m from the contact dark spots of phyllosilicates begin to appear. These spots are composed of aggregates of chlorite and muscovite which Pattison and Tracy (1991) suggest represent altered cordierite poikiloblasts. Within another 100 m extensive recrystallization is evident from the rapid loss of fissility along strike. In the final 120 m leading up to the contact on the side of Craig More, there is total loss of fissility and massive hornfelses occur containing assemblages with cordierite and K-feldspar. Muscovite has declined in abundance by this stage and the rock is very hard with a purplish colour on fresh surface, in marked contrast with the greenish-grey colour of the soft Aberfoyle Slate outside the aureole.

The contact of the hornfels with the intrusion is well displayed on the wooded slopes east of Craig More. Here a coarse-grained slightly pink granodioritic rock exposed on the lower ground is capped by the hornfels. A contact between chilled dark diorite and high-grade hornfels can be seen, although there is little visual distinction

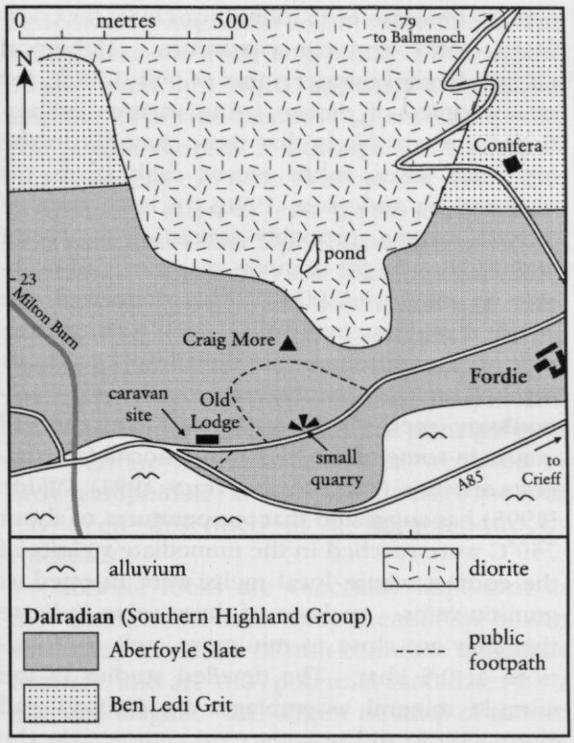


Figure 8.27 Map of the area around the Craig More GCR site, Comrie pluton, adapted from MacGregor (1996).

between these lithologies at the immediate contact. The contact appears to be at a shallow inclination, and it seems that the present exposure level is not far from the original pluton roof. White granitic veins cut the hornfelses and may be evidence of local anatexis.

Micrograndioritic dykes (formerly termed 'porphyrites') radiate from the pluton and many can be seen cutting the aureole rocks. Sulphide is quite abundant locally in the major intrusions and this pluton was actively explored for mineralization in the 1980s.

Craig More is also a good vantage point to view the line of the Highland Boundary Fault which runs ENE–WSW about 1 km south of Comrie essentially along Glen Artney. Small movements on this fault are still felt and one of the first seismometers was built by villagers in Comrie.

Interpretation

The diorites of the Comrie pluton vary considerably in their mineralogy, but include two-pyroxene diorites. These are important because several geothermometric calibrations exist for coexisting ortho- and clinopyroxenes. Mahmood (1986) derived temperatures of 950–1100°C for two samples of diorite using various calibrations; it seems likely that these may be on the high side given more recent calibrations (as reviewed by Anderson, 1996). A large mass of dioritic magma, probably consisting largely of melt judging by the textures, was intruded probably in excess of 900°C. This generated the *c.* 400 m-wide metamorphic aureole around the pluton. Conditions inside the aureole probably reached melting temperatures locally, as the granophyric intergrowth texture of K-feldspar and quartz in some of the high-grade hornfelses suggests anatexis (Pattison and Tracy, 1991). Wilde (1995) has suggested that temperatures of about 750°C were reached in the immediate vicinity of the contact where local melts were injected as granitic veins. Analyses of these veins indicate that they are close to minimum melt compositions at 0.5 kbar. The detailed studies of the aureole mineral assemblages by Pattison and Harte (1985) did not place an estimate on the geobarometric conditions, except that the aureole was at lower pressures than the Ballachulish aureole, which they suggested tentatively was between 2.5 and 4 kbar.

The Craig More outcrops provide an outstanding example of a low-pressure aureole in pelitic rocks and, although there are still many uncertainties about the precise pressure and temperature conditions and other factors such as the role of water, progress in these areas is being facilitated by new technological and theoretical developments. The Comrie aureole will continue to be an important case study for metamorphic petrologists.

These outcrops also provide a good example of a Caledonian pluton exposed close to its original roof. The low apparent pressure of the aureole indicates emplacement at a shallow level in the crust, but the reason for the trend of the pluton across the regional strike is not known.

Conclusions

Country rocks close to the southern end of the Comrie pluton, in the vicinity of Craig More, exhibit one of the most spectacular contact metamorphic aureoles in Britain. The GCR site has historical importance for early studies of contact metamorphism and has been cited as a type example in a recent classification of contact aureoles. Pelites can be traced over a distance of about 400 m, from those showing no evidence of contact metamorphism, through rocks with a range of mineral assemblages, to rocks with evidence of melting. The aureole has several distinctive mineral assemblages, although the absence of garnet is notable. These assemblages have provided useful information on the conditions of metamorphism, up to contact melting at about 750°C adjacent to a body of dioritic magma, which was probably intruded at a temperature of at least 900°C.

Diorites and granodiorites are the main intrusive rocks at this site, and the pluton is exposed just beneath the level of the original roof.

GARABAL HILL TO LOCHAN STRATH DUBH-UISGE (NN 304 177–282 158)

W. E. Stephens

Introduction

The Garabal Hill–Glen Fyne igneous complex is well known worldwide from the pioneering study of Nockolds (1941). It is also celebrated for its wide and continuous range of rock types from peridotite to granite. The contribution of Nockolds, apart from publishing one of the first detailed geochemical studies of a plutonic complex, was to explain the whole sequence of rocks in terms of 'crystallization differentiation' of a pyroxene-mica diorite parental magma. This process generated basic and ultrabasic cumulate rocks and more acid differentiates along a liquid line of descent, essentially the same process as that now known as 'fractional crystallization'. This essentially closed system model for the petrogenesis of such complexes has been widely applied. Nockolds' paper influenced most studies of compositional diversity in granitic complexes worldwide for three subsequent decades and is still often cited as a classic study (e.g. Atherton, 1993).

The complex, which is a member of the South of Scotland Suite, was emplaced into Dalradian metasedimentary rocks of the Southern Highland Group at about 429 Ma. Compositional diversity is the most important feature of this complex, with four bodies of peridotite located within several varieties of diorite and gabbro. Peridotites are virtually absent from late

Caledonian granitic complexes elsewhere and their presence is important in understanding the petrogenesis of the more basic members of such complexes. The main mass of granodiorite is porphyritic, although megacrysts are lacking in the east. Appinitic rocks are closely associated with the granodiorites, and large numbers of other appinitic bodies are known from this area (Anderson, 1935a; Anderson and Tyrell, 1937).

The first account of the complex was published by Dakyns and Teall (1892) who were struck by the petrological variety, which they attributed to the differentiation at depth of a single parental magma. This was a rather advanced view for its day. This was followed by the Geological Survey memoirs (Gunn *et al.*, 1897; Hill, 1905), and a detailed study of the ultramafic and basic varieties of the complex (Wyllie and Scott, 1913). In the following eight decades or so, the only paper specifically to address the origin of this complex with new data was that of Nockolds (1941). Although Nockolds' model is often cited, it should be viewed with some caution in the light of modern studies. Most late Caledonian plutons that have been studied in any geochemical detail show evidence of significant open-system behaviour (e.g. Halliday *et al.*, 1980) and a compilation of the available but rather meagre Sr isotopic data for Garabal Hill (Summerhayes, 1966; Harmon and Halliday, 1980) suggests that the granodiorite probably has a different origin to the rest of the complex.

Description

Garabal Hill is situated to the north of Loch Lomond and gives its name to the more petrologically variable part of the complex; the larger and more homogeneous mass of granodiorite occupies the high ground to the SE of Glen Fyne (Figure 8.28). The more basic rocks of the complex are separated from the main plutonic mass by the Garabal Fault, which in turn is truncated by the Glen Fyne Fault. The exposed area of the entire complex is 32 km^2.

The wide range of petrology has been adequately described in the papers cited above, but a summary is necessary here to convey the key feature of extreme petrological variation. The descriptions are based on Nockolds (1941) supplemented with modal and electron microprobe data from Mahmood (1986).

Ultramafic rocks crop out as discrete bodies, 100 m to 1 km across (Figure 8.28), and include peridotites, pyroxenites and hornblendites. The fresh ultramafic rock is typically a black peridotite (wehrlite) with approximately equal amounts of olivine (about Fo_{80}) and clinopyroxene (augite–diopside), although the content of clinopyroxene can drop to about one-third. The peridotite is often at least partly serpentinized (Figure 8.29). Other types of peridotite, including dunite, lherzolite and plagioclase-bearing varieties are also present, usually showing internal contacts with the main peridotite. In the pyroxenites, olivine is typically absent and orthopyroxene becomes more important, although clinopyroxene is still the principal mineral. Clinopyroxene is commonly replaced by brown amphibole, and in extreme cases the rock has been described as a hornblendite by Nockolds.

Gabbroic rocks are especially important as they are the most basic component of the pluton with clear evidence of non-cumulate magmatic textures, and are thus potential candidates for a parental magma. The largest outcrop of gabbro stretches for about 1.4 km around Lochan Srath Dubh-uisge and, after being cut out for about a kilometre by granodiorite, also forms quite a large mass at the southern end of the complex (Figure 8.28). The typical gabbro has abundant clinopyroxene, partly or largely replaced by actinolitic amphibole or brown hornblende. Hypersthene-bearing varieties are known; biotite is present in the gabbros close to late veins of granodiorite.

Diorites were the favoured parental magma of Nockolds, specifically the pyroxene-mica diorite. This latter rock, found in the east of the complex (Figure 8.28), contains more clinopyroxene (about 17%) than orthopyroxene (7%), biotite (about 17%), and pseudomorphs after olivine. About half of the rock is plagioclase of about An_{41} composition. As is typical in this complex, clinopyroxene is commonly replaced by amphibole. Hornblende-rich diorites are also present in the eastern part of the complex, and show marked variations in grain size which Nockolds described as coarse appinitic diorite (coarse-grained), to medium appinitic diorite (medium grained) to fine-grained quartz diorite. There is some debate as to whether the amphibole is primary or secondary in these rocks; although many amphibole crystals are idiomorphic in form and would appear to be primary, others clearly show evidence of replacement. Some diorites are also remarkably rich in xenoliths

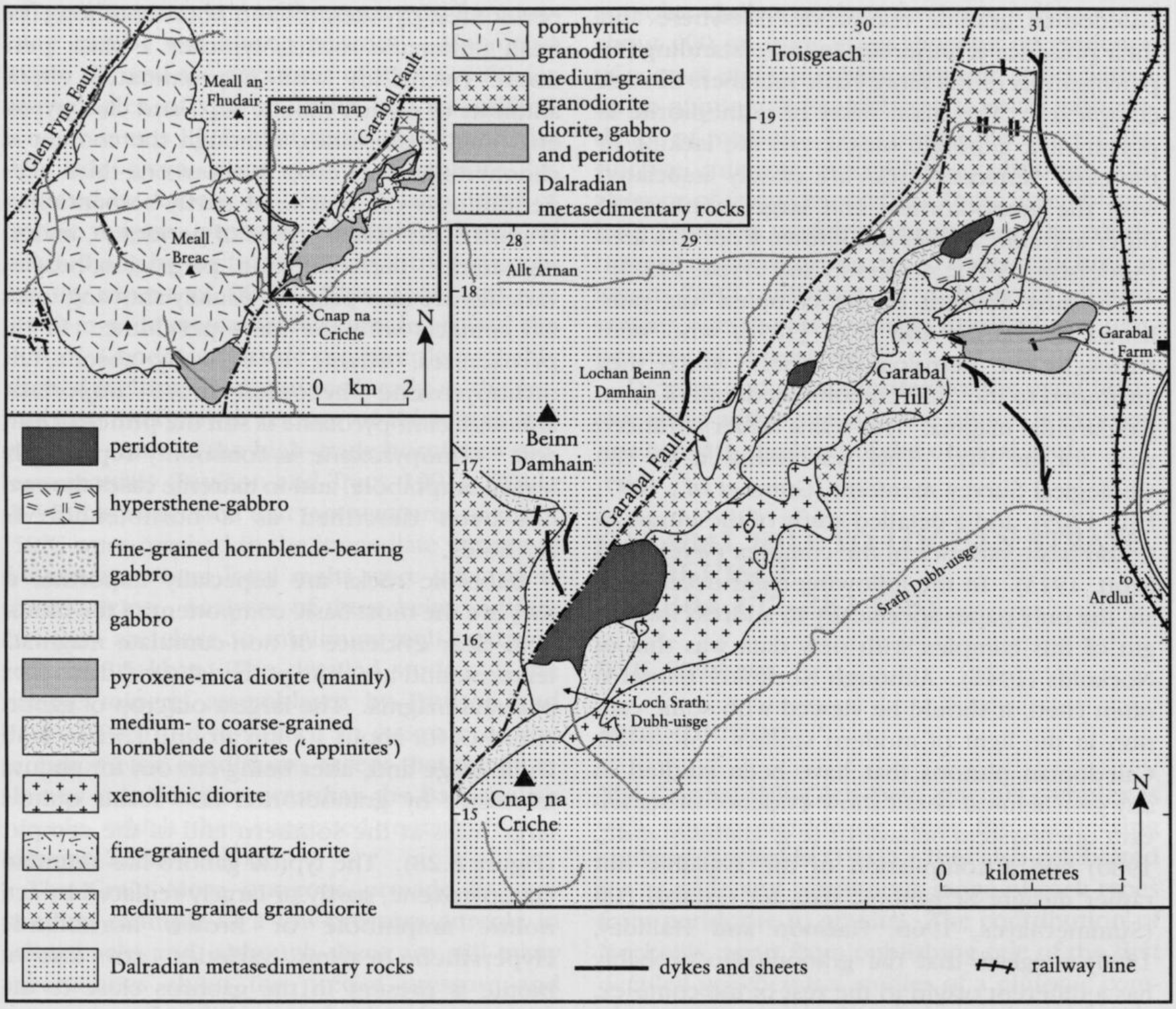


Figure 8.28 Map of the Garabal Hill–Glen Fyne igneous complex (after Nockolds, 1941).

(Nockolds' xenolithic diorite) which appear to be dominantly of basic igneous rocks.

The final intrusive phases consist of granodiorites. The medium-grained granodiorite is earlier than the porphyritic granodiorite, occurring both on the eastern margin of the main Glen Fyne intrusion and as a separate strip SE of the Garabal Fault. This facies contains hornblende and biotite with quartz, K-feldspar and plagioclase. A major feature is the abundance of xenocrysts of plagioclase, augite and amphibole, making it a very heterogeneous rock. Nockolds interpreted these xenocrysts as 'earlier igneous material' which he believed to have had a significantly modifying effect on the overall composition. The main porphyritic 'granodiorite' is a rather more homogeneous biotite granite, with a porphyritic character imparted by megacrysts of alkali feldspar.

Interpretation

Age relationships within the complex have been established by cross-cutting internal contacts, veins of late granodiorite, and xenolithic inclusions. It is clear on these criteria that the ultramafic rocks are early and are cut by the gabbros, which in turn provide xenoliths for the diorites, which are intruded by the granodiorites. Thus the age sequence appears closely to match the order of increasing acidity. The age of emplacement is also well constrained. Rogers and Dunning (1991) found the U-Pb age on an appinitic diorite to be 429 ± 2 Ma (zircon) and 422 ± 3 Ma (titanite). Combining these data with the Rb-Sr biotite-whole rock age of

406 ± 4 Ma (Summerhayes, 1966), it may be concluded that emplacement took place at about 429 Ma, followed by cooling through 600°C at 422 Ma, down to about 300°C at 406 Ma.

The geochemical study of the complex by Nockolds revealed a gradual change in composition from the peridotites (as low as 42% SiO_2) to the granites at 68% SiO_2, which led to his classic interpretation of closed system differentiation. Nockolds reasoned that rocks more basic than his proposed parental pyroxene-mica diorite magma must be the products of mineral accumulation, as evidenced by the abundant mafic minerals in the appinitic diorites, the gabbros and especially in the peridotites. The differentiated magmas went on to evolve into the granodiorites. Mahmood (1986) tested this hypothesis with numerical models of the compositions and found a gabbro parental magma to provide a better model for the observed compositions, although no simple closed-system fractionation model tested was capable of generating the granodiorite compositions. Mahmood also provided new trace element data that contrasted with the major oxides in not describing single smooth linear trends. The trace element data are therefore difficult to reconcile with a simple liquid line of descent, although they do provide evidence of cumulate processes (exceptional Ni- and Cr-enrichments in the peridotites). This evidence is not completely unambiguous, but it is likely that the granodiorites evolved quite separately from the main gabbro–diorite series. The data also suggest that the gabbros and diorites represent quite distinct magma series.

One of the very early applications of the Rb-Sr isotope technique to the study of granite plutons was performed on Garabal Hill (Summerhayes, 1966). By modern standards the precision of the age and initial ratio calculations is rather poor. Nevertheless the range of initial ratios

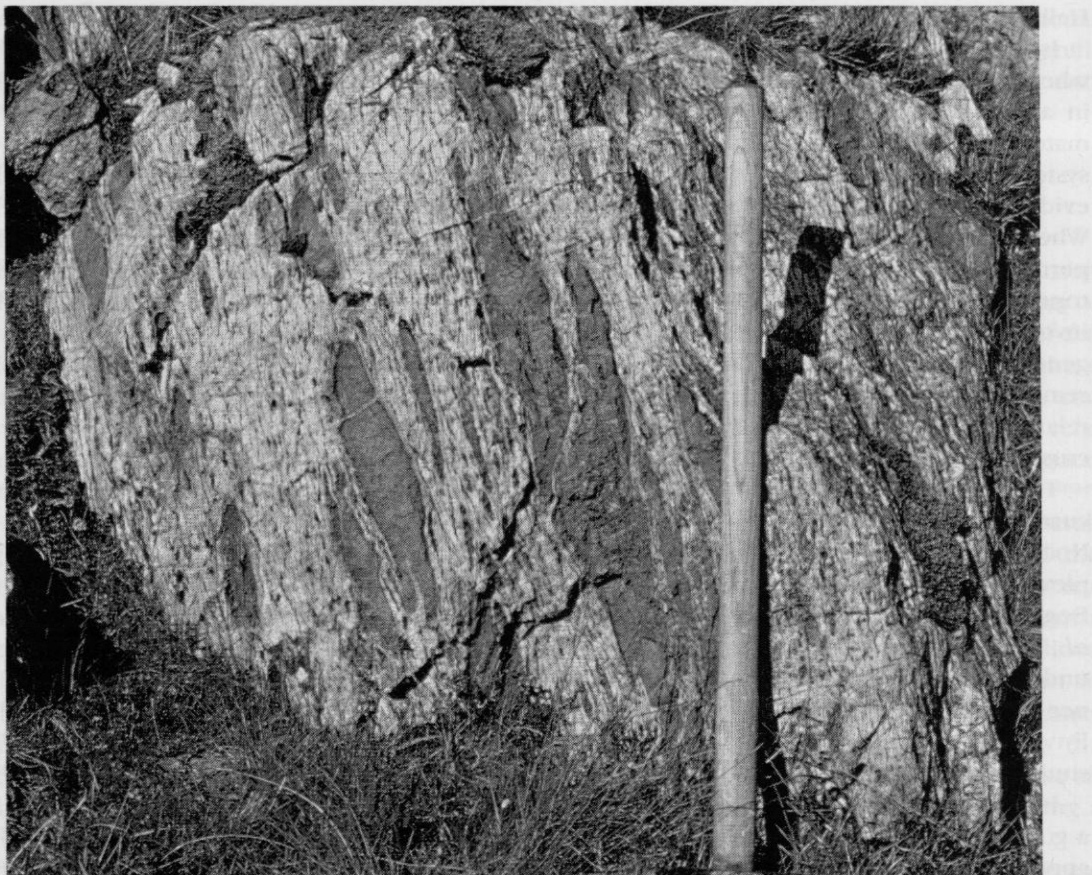


Figure 8.29 Serpentinized peridotites (wehrlite) at Lochan Strath Dubh-uisge, Garabal Hill–Glen Fyne igneous complex. (Photo: W.E. Stephens.)

measured is so large as to be significant in terms of the petrogenesis. Summerhayes found that the ($^{87}Sr/^{86}Sr$) initial values of all the uncontaminated components of the complex are the same within error, around 0.705. He noted, however, that several samples of the medium-grained granodiorite have higher values of this ratio (about 0.710) and concluded that these had the same parental magma as the main complex but were contaminated by local Dalradian metasedimentary rocks. This is consistent with the abundance of included xenoliths, as noted by Nockolds (1941). These are important petrogenetic conclusions but must be viewed in the context of modern Sr isotope studies in which variations of an order of magnitude smaller are taken to have petrogenetic significance. A higher precision isotopic study of a single sample from the medium-grained granodiorite, the area of contaminated granodiorites studied by Summerhayes, gave a ($^{87}Sr/^{86}Sr$)initial value of 0.7074 and $\delta^{18}O$ of 10.4‰ (Harmon and Halliday, 1980).

Isotope ratios are now used routinely to test whether complexes such as Garabal Hill evolved in a closed system (i.e. no addition of exotic material to the parental magma) or in an open system, in which case the contaminant is usually evident in changes to the isotope ratios. Whereas the old data of Summerhayes do not permit a rigorous test, the newer Sr and O isotope data are strong indicators of a significant involvement of evolved crustal material in the genesis of the granodiorite magmas, while the remainder of the complex appears to have the relatively primitive signature of young basic crust and/or mantle sources.

The trace element and limited isotopic data currently available do suggest therefore that Nockolds' model is inappropriate for this complex. However, there are other plutons (e.g. the Boggy Plain pluton of SE Australia, Wyborn *et al.*, 1987) where melts can be clearly shown to undergo crystal–liquid fractionation in the manner envisaged in 1941 for Garabal Hill–Glen Fyne, so that the wider conclusions of Nockolds' study remain valid to the present day.

In a further study, Garabal Hill was chosen as a good example in which to investigate the disappearance of Ca-poor pyroxenes from crystallizing calc-alkaline magmas (Cawthorn, 1976). Cawthorn concluded from petrographical evidence that the replacement of the assemblage calcic pyroxene–calcium-poor pyroxene–plagioclase by amphibole–plagioclase in the more evolved rocks is explicable in terms of increasing fugacity of water, during differentiation of a basic magma.

Conclusions

The Garabal Hill–Glen Fyne complex shows the greatest variety of 'granitic' rocks in any one complex in the Caledonian of the British Isles. An orderly sequence of intrusion from basic to acid magmas can be demonstrated and the complex is an important site for the testing and developing of modern ideas on the origins of granitic rocks.

A model in which a single dioritic parental magma underwent differentiation by the removal of crystals as they formed, causing the residual magma to change composition along a 'liquid line of descent' was proposed by Nockolds in 1941. This very detailed study was widely acclaimed and the ideas were applied to other plutons worldwide. The influence of the study has undoubtedly been seminal, but critical examination of new geochemical and isotopic data from the Garabal Hill–Glen Fyne complex suggests that the model is oversimplified and that here, more than one different magma and modification by crustal contamination may have been involved. However, the original concept, which subsequently became known as 'fractional crystallization', has been shown to be valid for other plutons elsewhere in the world.

LOCH DEE (NX 458 761–466 847)

W. E. Stephens

Introduction

Loch Dee is located at the southern end of the Loch Doon pluton, which is one of the finest examples in Scotland of a zoned pluton showing inwards progression from a dioritic margin to an acid interior. The Loch Doon pluton stands out for the regularity of its zonation pattern over a very wide compositional range. This regularity has led to the suggestion that the zonation developed *in situ*. Another significant feature of the site is that the intermediate rocks include some of the best examples of hypersthene-mica diorite, the rock type considered to represent the parental magma for the Caledonian plutonic series in the influential model of Nockolds (1941) (see the Garabal Hill to Lochan Strath Dubh-uisge GCR site report).

The pluton was first recognized by the Geological Survey (Peach and Horne, 1899), with Teall (in the same volume) identifying the wide petrological range, which he attributed to differentiation in a deep-seated magma chamber prior to emplacement. The regularity and composite nature of the zonation within the pluton was demonstrated by Gardiner and Reynolds (1932) using a combination of mapping, petrography and density measurements, and the map of the complex has changed only in minor details with subsequent studies (although some of the rock nomenclature has been updated). Gardiner and Reynolds (1932) argued for separate intrusion of three successive magma pulses of increasing acidity.

In the 1950s the 'granitization' and 'basic front' transformationist theories of Doris Reynolds were applied to this pluton by McIntyre (1950), Rutledge (1952), and Higazy (1954) who argued on compositional grounds that the complex could be derived through solid-state metasomatic modification of the surrounding metasedimentary rocks. The magmatic versus replacement controversy over the origin of granites was largely settled in favour of the magmatists by the end of the 1950s, and a detailed study of the southern half of the complex (including the area around Loch Dee) by Ruddock (1969) returned to the magmatic view of petrogenesis for the pluton. He interpreted new whole-rock geochemical analyses as supporting the derivation of the complex by differentiation of a single parental magma of intermediate composition. Brown *et al.* (1979), also using a geochemical approach, concurred that a single parental magma was responsible for the complex. They identified the parental magma as monzodioritic, and postulated a two-stage fractional crystallization process. In contrast, Tindle and Pearce (1981), using an approach based largely on whole-rock trace element data, proposed that there had been two distinct parental magmas that evolved by fractional crystallization. These authors proposed that this fractional crystallization occurred *in situ* and the pluton has been widely cited subsequently as a leading example of in-situ fractional crystallization. Halliday *et al.* (1980) showed that the petrogenesis was even more complex, having identified distinctive isotopic signatures within and between the various plutonic members. Most marked is the variation in the oxygen isotope composition from the more primitive outer members to the more evolved interior which was attributed to increasing degrees of contamination of the magmas by metasedimentary rocks.

The pluton was emplaced into Ordovician metasedimentary rocks of low metamorphic grade at 408 ± 2 Ma, according to a mineral-whole rock Rb-Sr isochron (Halliday *et al.*, 1980) which is in agreement with U-Pb ages of 406 ± 2 and 410 ± 1 Ma obtained from single zircons (J. A. Evans in Floyd, 1997).

The Loch Doon pluton is important for understanding the origin of petrological zonation, there being differing views on the mechanism and the extent to which such processes can occur *in situ*. The Loch Dee site was selected for the GCR because it encloses all the important petrological variation in the southern part of the pluton. In this account the IUGS rock names of Le Maitre (1989) are applied using the modal analyses of Mahmood (1986), leading to significant differences with those of Gardiner and Reynolds (1932) and Brown *et al.* (1979).

Description

The hour-glass shaped Loch Doon pluton (Figure 8.30) is located between the Rhinns of Kells and the Merrick in Galloway. Much of the pluton forms low boggy ground between these hills, but the dioritic margins in the south and NW and the central ridge of granite form relatively positive features with moderately good exposure.

The outer contacts of the pluton are generally steep to vertical, but in the vicinity of the dioritic rocks of Loch Dee (Figure 8.30) contacts are much shallower and appear to represent a roof zone of the pluton (Stephens and Halliday, 1979). The evidence for this can be seen in small waterfalls that mark the contact zones between the diorite and country rocks in the White Laggan Burn and its tributaries. These all lie at similar topographical levels, suggesting a relatively flat, roof-like contact.

Petrological variation is concentric (Figure 8.30). There is an outer discontinuous zone of dark-coloured diorites, notably two-pyroxene-biotite diorite (fine- and medium-grained varieties with hypersthene, augite and minor olivine) and medium-grained hornblende-biotite diorites. Close to the contact south of Loch Dee these diorites are commonly quite xenolithic enclosing fragments of country rock. Good exposures of these xenolithic varieties, as well as the more normal fine-grained and medium-grained diorites, may be found in the road cuttings in the forestry plantations of this area.

The main mass of the pluton is granodiorite, with a tendency to form the low, poorly exposed ground. The rock is grey, medium- to coarse-grained, with abundant biotite and some hornblende as the principal mafic phases. The nature of the contact between the granodiorite and the dioritic facies is not clear; in places it appears to be quite sharp, but elsewhere a narrow transition zone is present. Passage to the central granite, which forms the ridge of high ground including Craiglee, Mulwharchar and Hoodens Hill, appears to be entirely gradational in the field, and no evidence of a sharp contact has been found. These white to buff-coloured granites have biotite as the only primary mafic phase and cordierite has been recorded in some microgranites at the very core of the pluton (Tindle and Pearce, 1981).

Interpretation

The main point of interest in this pluton is the exceptionally fine petrological variation, and an understanding of the origin of this variation requires combining field studies and geochemistry. The field evidence suggests a steep-sided plutonic body for the most part, except around the diorites which appear to form a roof zone. Three main facies make up the bulk of the pluton, namely diorite, granodiorite and granite. Each shows some internal variation, and the internal contact between the granodiorite and granite, in particular, is a rather broad transitional zone. The overall trend is one of increasing magmatic evolution towards the centre of the pluton.

In compositional terms, the pluton varies from the outer dioritic margin with about 57% SiO_2 (although rare samples of diorite in the NW have as little as 50% SiO_2) to the interior granite with about 72% SiO_2. The rocks are essentially metaluminous except for those with high SiO_2 levels, which are slightly peraluminous. Trace elements show no unusual enrichments or depletions relative to other South of Scotland Suite granitic rocks (Stephens and Halliday,

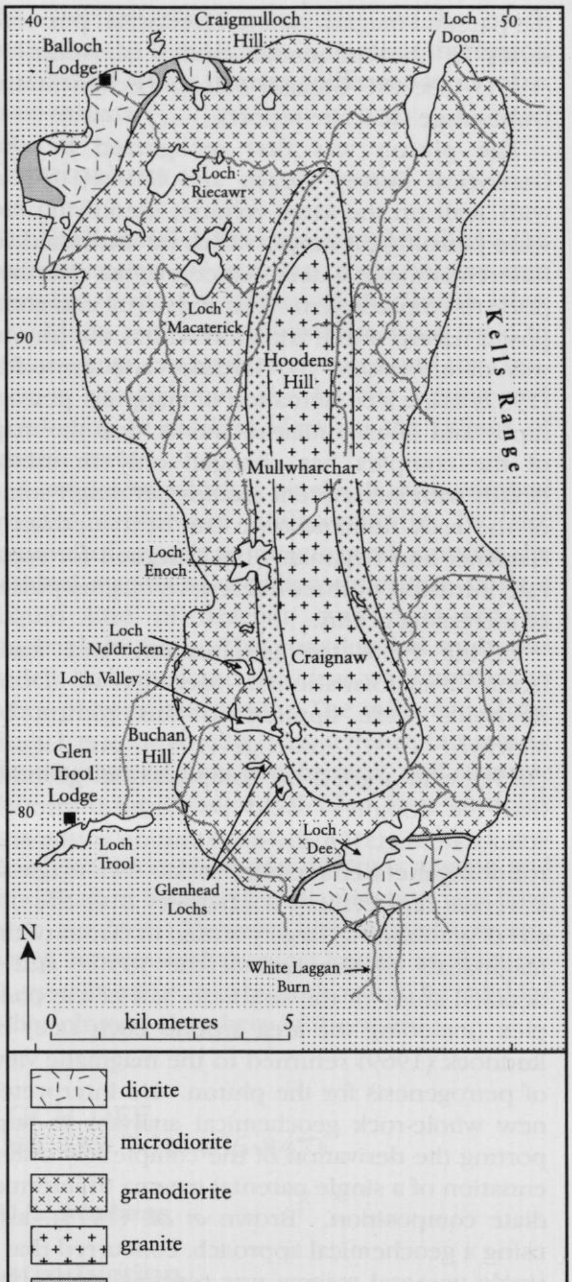


Figure 8.30 Map of the Loch Doon pluton, based largely on Gardiner and Reynolds (1932) with modifications from Ruddock (1969).

1984) and tend to vary smoothly through the sequence. Most trace elements decrease in abundance with increasing SiO_2 but Rb shows a continuous and marked increase as, to a lesser extent, does Th (Tindle and Pearce, 1981; Mahmood, 1986).

The concentric petrological variation is mirrored in the whole-rock isotopic composition. Initial $^{87}Sr/^{86}Sr$, for which most data are available, has the range of 0.7041–0.7051 in the diorites, 0.7052–0.7053 in the granodiorites, and increases from 0.7052 to 0.7059 in the granites (Halliday *et al.*, 1980). Whilst these differences are small, they are significant and systematic. There is a similar systematic variation in the oxygen isotopes, although on a smaller dataset. $\delta^{18}O$ varies from 7.8 to 8.3‰ in the diorites, is 8.3‰ in a single analysed granodiorite sample, and jumps to 10.2–10.3‰ in the granites (Halliday *et al.*, 1980). Nd isotopes may be more restricted with ϵNd values of –1 in the diorites and –1.4 in the granodiorites; no values have been determined for the granites (Halliday, 1984).

Most modern petrogenetic studies of this pluton have concluded that more than one magmatic pulse was involved in its construction, but the lack of clear internal contacts may indicate that at least some of the variation was formed by in-situ processes such as filter pressing and the accumulation of early formed crystals at the pluton walls (Tindle and Pearce, 1981). Such processes are isotopically closed systems and could not generate the observed isotopic variations described above; it would be necessary to involve some simultaneous assimilation of wall rocks in combination with fractional crystallization to account for such changes, as in the widely applied model of DePaolo (1981). It may be possible to apply this model satisfactorily to the geochemical variations in the Loch Doon pluton (there are no published attempts), but such a geochemical model would be inconsistent with the field evidence that the rocks requiring the greatest degree of assimilation are the innermost granites, those most isolated from the likely source of contamination. (It should be noted that the outcrops at the GCR site do not include the volumetrically less important 'Trend 1' and 'Trend 3' of Tindle and Pearce (1981) and thus have not been included in this discussion).

There is no model for the origin of the concentric zonation in the Loch Doon pluton that is consistent with all of the data. Isotopically, there is a requirement for two components in the magma generation, involving a primitive mantle-like component with another source which resembles the average of Southern Uplands Lower Palaeozoic crust (Halliday *et al.*, 1980). Where and how these components interacted is not known, but there is also strong evidence for the operation of fractional crystallization as proposed by Stephens and Halliday (1979) and Tindle and Pearce (1981).

In regional terms the Loch Doon pluton is the most southerly large pluton of the South of Scotland Suite. The relatively unevolved I-type granites of this suite have little evidence of significant crustal contamination. Farther south, plutons of the Galloway Suite are more complex with evidence for greater incorporation of Lower Palaeozoic metasedimentary rocks during their genesis (Halliday *et al.*, 1980) (see Clatteringshaws Dam Quarry, Lea Larks and Lotus quarries to Drungans Burn GCR site reports). One feature in common with many of the larger South of Scotland Suite granites is the presence of marginal pyroxene-mica diorites. Isotopic studies have shown that this facies is not the universal parental magma for the Caledonian granites as suggested by Nockolds (1941) and Nockolds and Mitchell (1948). Nevertheless it is important, as relatively anhydrous dioritic facies are not widely represented in granitic rocks of other orogens.

Conclusions

The Loch Dee GCR site was chosen as representing a key segment of the Loch Doon pluton, which has made important contributions to international studies of when and where compositional variation is developed in the history of a granitic pluton. Possible sites are *in situ*, by accumulation of crystals against the walls of the pluton and squeezing out of remaining magma towards the centre (filter pressing), or by fractionation in a feeder magma chamber beneath the pluton. Other possible factors include contamination during ascent, and heterogeneities in the original source. Presently no single model fully accounts for the variations within the Loch Doon pluton; it is expected that the Loch Dee GCR site will continue to provide new and valuable constraints in developing a fully consistent model, and that this will have implications for many plutons elsewhere in the world that show similar concentric petrological zonation.

CLATTERINGSHAWS DAM QUARRY (NX 548 754)

W. E. Stephens

Introduction

The Fleet pluton

The Cairnsmore of Fleet pluton (nowadays usually called the Fleet pluton) is one of three large and several small granitic bodies in the Southern Uplands of Scotland that comprise the Galloway Suite. The pluton lies within a broad zone of ductile shear, the Moniaive Shear zone, that affects Llandovery age sedimentary rocks of the Gala Group (Phillips *et al.*, 1995a). Weak to moderately developed pre-full crystallization fabrics, transitional into high-temperature fabrics within the pluton and shear-fabrics within the contact aureole (Barnes *et al.*, 1995), argue the case for emplacement during the final stages of sinistral movement within the shear zone. The Orlock Bridge Fault, close to the NW margin of the pluton, is a late brittle structure that developed on the NW edge of the shear zone.

Most of the plutons of the Galloway Suite have similar mineralogical and compositional characteristics but the Fleet pluton is distinctly different. This uniqueness, coupled with its young age, has important implications for the petrogenesis of the relatively late Caledonian granites and the reconstruction of their plate tectonic environment. The pluton has two main granite facies, first established by Gardiner and Reynolds (1936), namely biotite granite and biotite-muscovite granite. The distribution of these facies was mapped by Parslow (1968) who further subdivided the biotite-muscovite granite facies into fine- and coarse-grained varieties, separated by a mappable sharp internal contact (Figure 8.31). Parslow (1971) also mapped the modal mineralogy and major oxide composition, and showed that some key parameters are concentrically zoned. The internal and external contacts were modelled from gravity anomalies, which suggest that the pluton continues to a depth of at least 11 km beneath the present surface (Parslow and Randall, 1973). In a regional study of the pluton and its environs Cook (1976) confirmed the general structure of the pluton and argued that extensive base metal mineralization in the south-western aureole is related to a shallow roof zone, in agreement with the suggestion from gravity anomalies of a western extension of the granite and a subsurface cupola (Parslow and Randall, 1973).

In a regional context the Fleet pluton is petrologically and geochemically unique (Stephens and Halliday, 1984). It has many of the characteristics of S-type granites (Chappell and White, 1974), indicating derivation of the magmas from a metasedimentary source, unlike the other late Caledonian granites in Scotland, which are all I-type and derived from meta-igneous sources (Stephens and Halliday, 1984). Isotopic compositions are generally similar to the Lower Palaeozoic host rocks suggesting that such a protolith may have provided a significant proportion of the granitic magmas from which the Fleet pluton crystallized (Halliday *et al.*, 1980).

The pluton has been dated by various methods. A U-Pb determination on zircon separates gave 390 ± 6 Ma (Pidgeon and Aftalion, 1978) within error of an Rb-Sr whole rock isochron age of 392 ± 2 Ma (Halliday *et al.*, 1980). A new unpublished zircon age is apparently similar (J. A. Evans, quoted by Barnes and Fettes, 1996). As the local metamorphic grade was low, these results establish the emplacement of this pluton at around 392 Ma, clearly Early Devonian, and the youngest reliably dated Caledonian pluton of mainland Scotland.

These data establish this pluton as somewhat anomalous in its context as a late Caledonian granite emplaced north of the Solway–Shannon line, which is usually taken as the line of the Iapetus Suture. Looking farther afield, the Fleet pluton is seen to have far stronger geochemical affinities with the plutons emplaced south of this line, that is those of the English Lake District and SE Ireland. It has been suggested that the source of the Fleet magmas was the same as those of the Lake District plutons (Stephens and Halliday, 1984) with the implication that magma genesis occurred after closure of the Iapetus Ocean and during underthrusting of the Southern Uplands by the leading edge of the southerly continent, and this is supported by more recent Pb isotope data (Thirlwall, 1989).

The importance of this pluton is its unique age and composition for a northerly late Caledonian granite, and its affinity with its southerly equivalents. The pluton is likely to provide important constraints on the timing and structure of the end-Iapetus closure and collision events. Two GCR sites have been selected, one to represent the more primitive outer por-

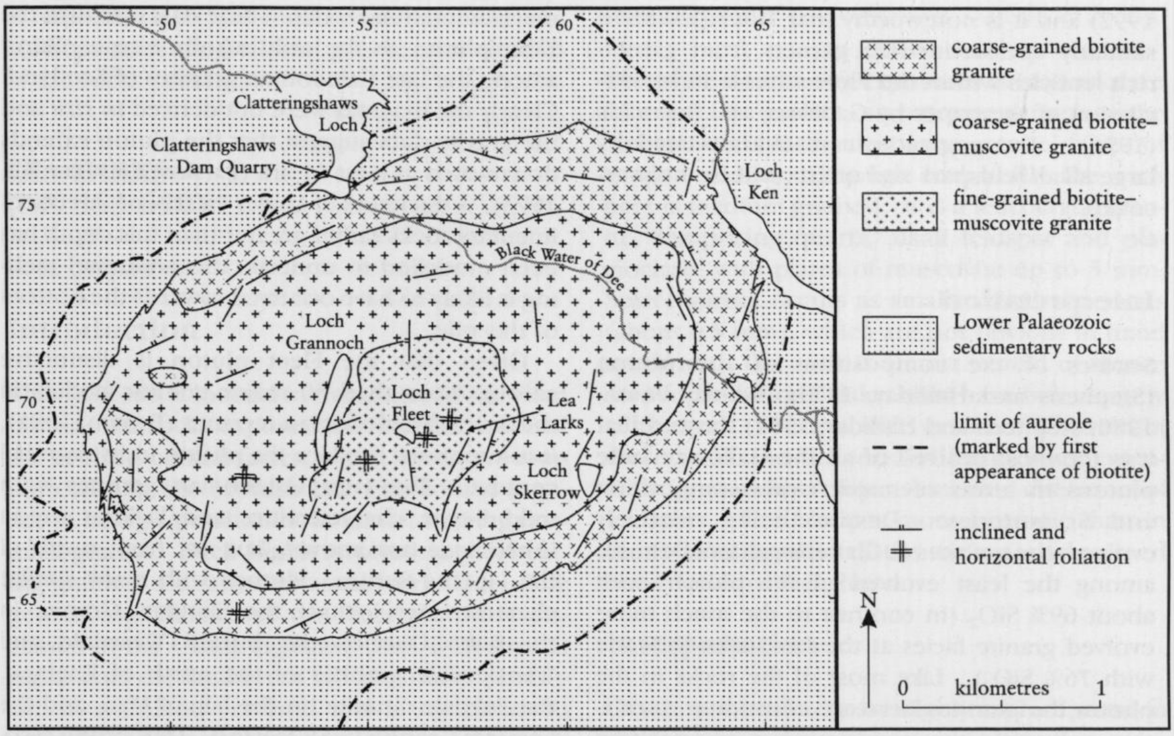


Figure 8.31 Map of the Fleet pluton, adapted from Parslow (1968), showing the locations of the Clatteringshaws Dam Quarry and Lea Larks GCR sites.

tions (Clatteringshaws Dam Quarry) and one to represent the more evolved central facies (Lea Larks).

Clatteringshaws Dam Quarry GCR site

The quarry and road cuttings at Clatteringshaws Dam (Barnes and Fettes, 1996) provide accessible and representative exposures of the marginal biotite granite facies of the pluton, which here is injected with aplite and pegmatite veins. The outer contact of the pluton with the metasedimentary rocks is also well exposed.

Description

The contact zone of the pluton is traversed by the road cuttings at Clatteringshaws Dam. Here the hornfelsed Silurian greywackes can be seen to dip northwards away from the pluton at about 40°, which is typical of that predicted by the gravity anomaly study (Parslow and Randall, 1973). The small quarry at Clatteringshaws Dam was cut in grey coarse-grained biotite granites, the outer facies of the zoned Fleet pluton, about 100 m from the outer contact (Figure 8.31).

This outer granite consists dominantly of alkali feldspar (microcline) and quartz. The alkali feldspars form quite large crystals (up to 5 cm) and are microperthitic; plagioclase is much less abundant and forms small crystals. Quartz forms large pools of strained polycrystalline aggregates. There is some biotite, usually chloritized, and some secondary muscovite replacing the alkali feldspars, but very few opaque minerals. The rock has a marked fabric with a strongly developed mortar texture in which strings of granulated quartz and mica develop around large 'islands' of alkali feldspar. This fabric gives the rock a foliation, obvious in the field, which can be traced throughout the pluton suggesting a relationship to its mode of emplacement. At this locality the foliation has a similar orientation to the foliation in the local hornfelsed country rocks.

Veins of aplite and pegmatite are common in both the quarry and the road cutting. The aplitic rocks are highly leucocratic bodies composed dominantly of alkali feldspar, plagioclase and quartz with minor chloritized biotite and accessory garnet. Analyses of these garnets show them to be unusually manganiferous (Macleod,

1992) and it is noteworthy that Tilley described similarly spessartine-rich garnets from garnet-rich lenticles within the Fleet aureole in his discussion of the paper by Gardiner and Reynolds (1936). The pegmatites are characterized by large alkali feldspars and quartz with some muscovite.

Interpretation

Studies of the composition of the pluton (Stephens and Halliday, 1979; Halliday *et al.*, 1980; Stephens and Halliday, 1984) showed that it is the most evolved of all the Galloway Suite plutons in terms of major oxide composition and Sr isotopes. Despite being relatively evolved, the granites at Clatteringshaws Dam are among the least evolved of the pluton, with about 69% SiO_2 (in contrast to the much more evolved granite facies at the Lea Larks GCR site with 76% SiO_2). Like most of the rocks in the pluton the granites here are corundum normative, reflecting the peraluminous composition and the dominance of micas among the mafic minerals. However, at this locality the abundance of normative corundum is low, at less than 1%. This granite also has the least evolved isotopic compositions of this pluton, with a $^{87}Sr/^{86}Sr$ initial ratio of 0.7062 (Halliday *et al.*, 1980) and ϵNd at this locality of –2.4 (Halliday, 1984). The oxygen isotope values for the whole pluton (including this site) are highly evolved, with $\delta^{18}O$ around 11‰, indicative of a source with a major sedimentary component (Halliday *et al.*, 1980). A lead isotope study (Thirlwall, 1989) showed that the Fleet pluton is enriched in $^{207}Pb/^{204}Pb$, a signature more typical of Lake District granites such as Skiddaw than the Scottish late Caledonian granites.

In a regional survey of the Scottish late Caledonian granites, Stephens and Halliday (1984) found that the Fleet pluton, and to a lesser extent the Criffel pluton, do not fit neatly into their classification (see Chapter 8: Introduction) and they were omitted. Most of the late Caledonian plutons are I-type granites, whereas Fleet has many of the important characteristics of an S-type granite (Chappell and White, 1974) indicating that a major part of its protolith was metasedimentary. This conclusion is supported by the Sr and oxygen isotopic data, which are also consistent with derivation of the magmas in large part from the local Silurian metasedimentary rocks. These data establish the Fleet pluton as the only wholly S-type pluton among the late Caledonian granites of Scotland. Clearly the magmas were not derived *in situ* and the gravity data suggest that the pluton extends downwards at least 11 km (Parslow and Randall, 1973). A thickness of Lower Palaeozoic metasedimentary rocks rather greater than this depth has been modelled to underlie this area, and melting is likely to have occurred towards the bottom of this pile.

Given that the Fleet pluton is distinctive among more than 50 major granitic bodies in the Scottish Caledonian terranes (Brown, 1991), it is important to place the pluton in its regional context. Two-mica Caledonian granites with mild S-type characteristics and lacking zircon inheritance are known, but not from north of the Iapetus Suture. Plutons with many similar characteristics include the Skiddaw Granite in the Lake District, the buried Weardale and Wensleydale granites of the north of England, the Foxdale Granite on the Isle of Man, and the Leinster Granite of SE Ireland. This strong association with plutons on the other side of the Iapetus Suture led Stephens (1988) to suggest that they had a common, rather young, immature sedimentary source and that they shared an end-closure tectonic environment in which the same source rocks became available on either side of the suture. This implies underthrusting of the southerly continent beneath the leading edge of the northern continent, i.e. beneath the Fleet pluton, and this is consistent with the geophysical interpretations of Beamish and Smythe (1986).

Conclusions

The Fleet granite pluton is unique among all the late Caledonian granites of Scotland, as a consequence of the change in source of magmas near the leading edge of the northern (Laurentian) continental landmass. Geochemical evidence strongly suggests an origin of the magma in rocks similar to those that currently host the pluton, but the pluton's rather greater affinity with those in the English Lake District points to a more southerly source. These associations have important tectonic implications for the events that followed closure of the Iapetus Ocean and the collision of the continents either side of the Iapetus Suture. The site is thus of major national importance for the conclusions that have arisen from mineralogical and geochemical studies of the rocks present.

LEA LARKS (NX 563 690)

W. E. Stephens

Introduction

This GCR site is located in the centre of the Fleet pluton; the rocks exposed are representative of the evolved central facies, which is very uncommon among the Scottish late Caledonian granites in being a peraluminous garnet-bearing two-mica granite. Such highly evolved garnet-bearing granites are rather unusual worldwide. The general significance of the Fleet pluton is discussed in the Clatteringshaws Dam GCR site. It represents the final event of Caledonian plutonism in mainland Scotland and is significant in providing important constraints on the end-stages of the Caledonian Orogeny and the closure of the Iapetus Ocean.

Zonation in the Fleet pluton takes the form of a small central facies of fine-grained granites within the main coarse-grained biotite granite and biotite-muscovite granite facies, as shown on Figure 8.31. There is a sharp contact between the inner and outer facies, and xenoliths of coarse-grained granite are found within the fine-grained, demonstrating that the central pulse is the last major intrusive event (Parslow, 1968). This central facies is the most evolved of the pluton and is particularly distinctive in compositional terms.

Small, apparently magmatic, garnets are present in the granites of this facies in the vicinity of this site. These are spessartines, similar to those described by Macleod (1992) in aplites from the marginal zones. Such garnets are usually associated with highly evolved granitic melts of appropriate bulk composition, probably as the result of extensive fractional crystallization (Speer and Becker, 1992).

The Lea Larks GCR site was selected as representative of the most evolved facies of the Fleet pluton. It is well exposed and accessible via forestry tracks. The rocks of this facies are rare, and have almost nothing in common petrogenetically with the other late Caledonian granites of Scotland.

Description

The white-weathering exposures at Lea Larks are of muscovite granite, an extreme variant of the 'fine-grained biotite-muscovite granite' facies of Parslow (1968), although technically the rock here is medium grained. It is a leucocratic granite, comprising quartz, alkali feldspar and plagioclase, with plates of muscovite up to 5 mm. Scarce garnet occurs as small, anhedral crystals (about 0.5 mm), which are not obvious in hand specimen. The rock is almost devoid of biotite save for some rare flakes that have been largely chloritized. There is little evidence of strain in these rocks and the textural features are essentially igneous apart from some late alteration of feldspars. The fabric is more isotropic than in the foliated granites of the main coarse-grained outer facies of the pluton.

Interpretation

Granites at Lea Larks are highly evolved, even in the broad context of the late Caledonian granites. They have about 76% SiO_2 and a normative composition of more than 95% quartz + orthoclase + albite, approaching the 2 kbar ternary minimum. About 2.5% normative corundum indicates a strongly peraluminous composition, which is reflected by the presence of muscovite. Most trace elements are strongly depleted relative to other late Caledonian granite plutons, and to the outer facies of this pluton. The sole exception is Rb, which reaches levels of over 500 ppm in some samples. Initial $^{87}Sr/^{86}Sr$ ratios of 0.7076–0.7109 are significantly higher than in the outer facies, but the oxygen isotopes are indistinguishable (Halliday *et al.*, 1980). Overall, the geochemical features suggest that the highly evolved composition was probably achieved by fractional crystallization, particularly through the removal of feldspars and accessory minerals.

The bulk composition of the Fleet pluton is peraluminous, and granites at the Lea Larks site are strongly so. Strongly peraluminous compositions suggest a pelitic source rock (Miller, 1985; White and Chappell, 1988) and the combined major oxide and isotopic composition of this facies are consistent with this interpretation (Halliday *et al.*,1980). However, such highly evolved compositions have also been attributed to fractional crystallization (Clarke, 1992); and Halliday *et al.* (1981), reviewing the origins of peraluminous compositions in granitic magmas, suggested that this may have involved subaluminous amphiboles. However, there is no evidence that amphibole ever crystallized from any of the magmas of the Fleet pluton and thus this mechanism can be discounted. It seems that the magma from which these muscovite granites formed was originally peraluminous, with S-type characteristics, and that it evolved through the fractional crystallization of feldspars.

Almandine garnets occur in earlier Caledonian granitic rocks of the Lake District (Firman, 1978b; see Chapter 4) and Connemara, Ireland (Bradshaw *et al.*, 1969). However, spessartine occurs only in highly evolved granitic rocks; in the British Caledonides it has been recorded only from aplites and pegmatites, from the outer marginal facies of the Cairngorm pluton (Harrison, 1988) and from Lea Larks. The presence of garnet, albeit in rather small abundance, is important as an indication of extensive fractional crystallization of peraluminous granite magmas (Speer and Becker, 1992). Garnets in granites have also been interpreted as refractory relics from the melting of a pelitic protolith (Green, 1976). However, the composition of the spessartine garnets at Lea Larks and the evolved compositions of the whole rock are more consistent with a magmatic origin. In an analogous pluton, Speer and Becker (1992) show such garnets to be late magmatic, crystallizing at about 650°C.

The significance of the Fleet pluton in terms of its tectonic setting during end-Caledonian times has been discussed in the Clatteringshaws Dam GCR site. The Lea Larks site represents the most evolved facies of the zoned pluton.

Conclusions

The Lea Larks GCR site represents one of the most highly evolved forms of granite found in the late Caledonian granitic suites of Scotland. The granite at Lea Larks contains garnet and the chemical composition of the rock suggests a long history of fractional crystallization, leading to the generation of a highly evolved melt through the separation of crystals from the magma. These processes are important for understanding the mechanisms by which certain elements (including economically important metals) become enriched in evolved magmas, and ultimately in fluids derived from them.

The compositions of these rocks also reveal that the source of the magmas had a major component of crustal sedimentary rocks not unlike those which presently host the pluton but also with similarities to those of the Lake District, suggesting that these may be present at depth beneath the present Fleet pluton.

Further study of these outcrops will improve understanding of how highly aluminous magmas evolve in their late stages and may also provide tectonomagmatic constraints on models for the closure of the Iapetus Ocean and subsequent collisional events.

LOTUS QUARRIES TO DRUNGANS BURN (NX 897 685–907 665)

W. E. Stephens

Introduction

The Criffel pluton

The Criffel pluton is an outstanding example of a granitic pluton that exhibits strong concentric zonation. This zonation has been well characterized in terms of petrology, geochemistry and structure. The origin of such zonation in granitic plutons has been the subject of controversy for many decades, and this pluton has contributed significantly to that debate. Criffel is also an important pluton because it lies close to the postulated suture line resulting from the closure of the Iapetus Ocean. It was emplaced soon after this closure, around 397 Ma ago (Halliday *et al.*, 1980) into low-grade greywackes and pelites of Silurian (Llandovery to Wenlock) age.

The original survey of the pluton mapped the external boundaries of the pluton but did not distinguish different facies (Horne *et al.*, 1896). Petrological zonation was first demonstrated by Phillips (1956) in developing the idea of Macgregor (1937) who showed that the western part of the pluton consists of multiple phases of granite. Phillips also produced the first detailed map of the whole pluton and its aureole, and this remains the most detailed geological study of the area. Stephens and Halliday (1980), Stephens *et al.* (1985) and Stephens (1992) focused on the petrological and petrogenetic aspects and refined the two-fold classification of Phillips. Five more-or-less concentric zones based on the dominant mafic mineralogy are now recognized (Figure 8.32); from the least to the most evolved these are clinopyroxene-biotite-hornblende (CBH) granodiorite, biotite-hornblende (BH) granodiorite, biotite (B) granite, muscovite-biotite (MB) granite, and biotite-muscovite (BM) granite. The pluton and host rocks are also notable for their mineralization (Gallagher *et al*., 1971; Braithwaite and Knight, 1990), including uranium and other rare minerals.

Zonation of granitic plutons is a very common feature, but no consensus exists for its origin. Models to explain zonation include, among others, fractional crystallization, multi-pulse intrusions, magma mixing, variable degrees of restite separation, and contamination by assimilation. An isotopic study of zonation of the Criffel pluton demonstrated for the first time that closed-system process alone could not account for such zonation, at least in this pluton (Halliday *et al*., 1980; Stephens and Halliday, 1980). Crystals and melts may separate in a closed system from a parental magma in various ways; by crystal settling or wall-rock accumulation, by the separation of entrained restite, or by filter-pressing processes. The system becomes open when the parental magma is contaminated in some way, either by assimilation of wall rock during ascent or emplacement, or by the mingling and ultimately mixing with a different magma. The only way of confidently distinguishing open and closed systems is by means of isotopic ratios; these parameters change little during closed-system processes but will disclose the open-system interaction of two magmas or magma + wall rock if these initially have significant isotopic differences. This methodology was first successfully applied to demonstrating the importance of open system processes at Criffel.

In terms of the widely used I- and S-type classification of granites (Chappell and White, 1974) Criffel is somewhat enigmatic. The early, outer hornblende-bearing facies (CBH and BH granodiorites) are undoubtedly I-types (derived from meta-igneous source rocks). The last, innermost member, the BM granite, has affinities with S-types (derived from metasedimentary source rocks), although it does not entirely fit in all of its features. The intermediate zones, the B and MB granites, are transitional in their characteristics. The pluton also provided mafic microgranular enclaves (igneous-textured xenolithic inclusions) for a study by Holden *et al*. (1987) which was the first to show that such enclaves can retain a Nd isotopic memory of a mantle or mantle-like source. The implications are either that mantle-derived material became involved in the crustal melting event (Holden *et al*., 1987) or that primitive magmas became incorporated into the granitic magma around the time of emplacement, as has been demonstrated elsewhere (Castro *et al*., 1990).

There are numerous analogous zoned plutons worldwide, especially in cordilleran batholiths such as the Sierra Nevada Batholith in California, and in almost every Phanerozoic orogenic belt. The importance of Criffel is not just that it was the first in which some of the important isotopic observations were made, but also because the nature of its zonation straddles the key I-type and S-type classification that has been widely applied since it was proposed in the mid-1970s (Chappell and White, 1974). Most plutons in Andean cordilleran settings belong to the I-type category and are believed to be the products of deep crustal melts (Chappell and Stephens, 1988) although some argue for a small or even a significant proportion of mantle material (DePaolo *et al*., 1992). Either way, I-types represent the melting of an igneous protolith and are generally characterized by metaluminous bulk compositions and the presence of hornblende and titanite. In contrast, S-type granites are typical of continent–continent collision orogens and are common in the Himalayas and the Hercynian of Europe. These granites are the products of melting metasedimentary protoliths leading to very different compositional and mineralogical characteristics, including peraluminous bulk composition, reflected in the presence of peraluminous minerals such as cordierite and muscovite.

The studies of Phillips and co-workers on this pluton have been important in terms of emplacement mechanisms and magma chamber dynamics (Phillips, 1956; Phillips *et al*., 1981, 1983; Holder, 1983). Several features such as enclave and mineral foliations, a steepening of the country rocks, and rotation of envelope fabrics into parallelism with the pluton margin, are suggestive of diapiric emplacement. However, as the amount of marginal deformation is very limited, Phillips *et al*. (1981) argued that emplacement was principally by stoping, and that convection in the magma was the cause of the primary mineral alignments and foliations. In discussion of their paper, Holder (1983) argued that the same features could be better

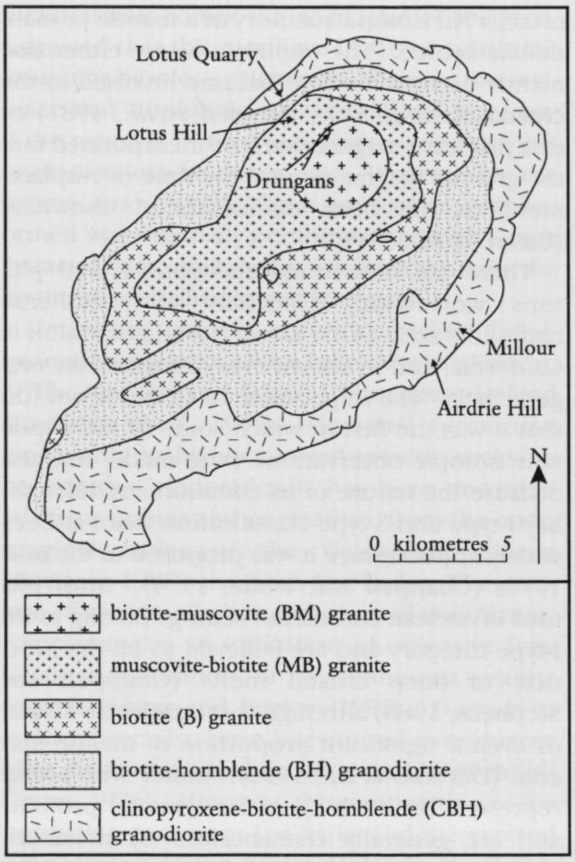


Figure 8.32 Map showing the principal petrological facies of the Criffel pluton.

explained by pluton ballooning. In an attempt to resolve the issue of the role of diapirism, Courrioux (1987) measured strain trajectories, strain gradients, and quartz fabrics over the whole pluton, which showed diapirism to have been the dominant emplacement mechanism for the second, inner magma pulse, and also possibly for the first.

The pluton is represented by two GCR sites: the Lotus Quarries to Drungans Burn site illustrates the main rock types and the concentric zoning; and the Millour to Airdrie Hill site exposes the outer contact and marginal zones, which contain abundant mafic-rich enclaves of structural and petrogenetic importance.

The Lotus Quarries to Drungans Burn GCR site

This site provides a section through the main components of the Criffel zoned pluton. Lotus Quarry is located within granodiorites close to the northern contact, and represents one end of a traverse in which there is a rapid petrological variation through the other facies to the two-mica granites to be found in the vicinity of Drungans, near the evolved centre of the pluton (Stephens, 1992) (Figure 8.32). This variation takes place over the whole pluton (Stephens and Halliday, 1980), but the gradient of change is steepest in this traverse; SiO_2 increases by about 10% over approximately 2 km, or roughly 1% SiO_2 every 200 m (Figure 8.33). This site has been selected as it offers the shortest traverse over all the major plutonic zones (i.e. steepest gradient of change) with reasonable exposure.

Description

The site is described from north to south, being the logical progression from least to most evolved members of the pluton (Figure 8.32). Exposure is quite good on the northern flanks of Lotus Hill to Lotus Quarry, but less good southwards towards Drungans Burn; the effects of forestry are to obscure some outcrops while creating others in road cuttings.

In and around Lotus Quarry the grey, foliated granodiorites of the CBH facies are exposed. As is the norm for this pluton the foliation dips outwards, in this case quite steeply at about 70° to the NW. The granodiorites are similar petrographically to those described more fully at the Millour and Airdrie Hill GCR site, and here also there are mafic enclaves lying in the foliation plane. The clinopyroxene is invariably included within amphibole, often in apparent reaction relationship. South of the quarry for about 300 m the granodiorite evolves to a clinopyroxene-free facies of biotite-hornblende granodiorites. The next zone inwards is normally the biotite granite facies but this is cut out in this area. Southwards, almost as far as Drungans, is the zone of muscovite-biotite granites. On Lotus Hill, a contact between this facies and the hornblende granodiorites can be located to within a few metres and the sharp junction is preserved in local boulders. This is important evidence that the pluton was emplaced as multiple pulses of magma.

Small knolls in the field west of Drungans cottage consist of the biotite-muscovite granite facies, but exposure is too poor to establish its relationship with the muscovite-biotite granite. The abundant large crystals of muscovite in the

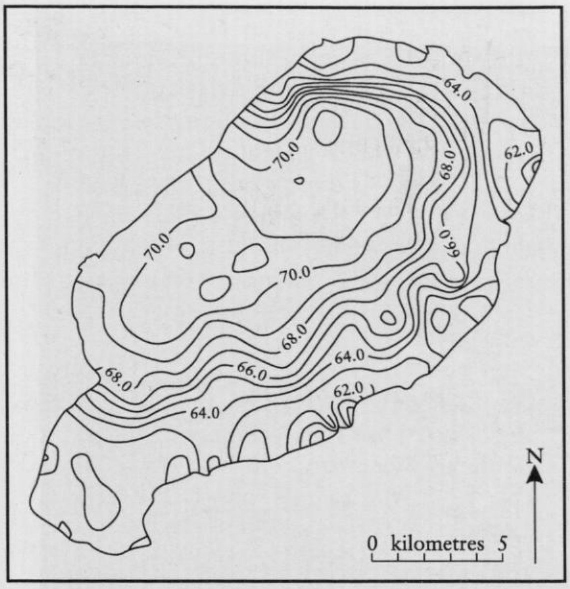


Figure 8.33 Contour map of SiO_2 variation in the Criffel pluton.

BM granite are magmatic on the basis of their igneous textures (Figure 8.35) and these are well seen in exposures at Drungans. About another 1.5 km SW of Drungans, on the northern end of Long Fell ridge, is the evolved core of the pluton in which muscovite is dominant with very little biotite present. In fact, biotite is normally extensively chloritized in this facies.

The contrast between the two ends of the traverse is illustrated in Figure 8.34 a, b, in which the grey, strongly foliated CBH granodiorite with mafic enclave is compared with the structurally more isotropic pink BM granite with abundant alkali feldspar and very few mafic minerals.

Interpretation

In order to understand the origins of zoning and the implications for the petrogenesis of such plutons it is essential to integrate the field data with the geochemistry. In this traverse the only evidence for an internal contact has been found between the MB granite and the BH granodiorite. Internal contacts between facies variations within the granodiorites (CBH to BH granodiorites) and within the granites (B to MB to BM granites) have never been located and it is presumed that these are gradational. However the sharp MB granite–BH granodiorite contact (which in places cuts out the B granite) shows that the granites were emplaced as a later magmatic pulse after the granodiorites had largely or entirely consolidated. This is consistent with the structural evidence for diapiric intrusion of the inner pulse discussed under the Millour and Airdrie Hill GCR site. The excision of the biotite granite leads to steepening of the compositional gradient in the region of the GCR site but elsewhere in the pluton even this boundary appears to be transitional, as described by Stephens and Halliday (1980).

Whole-rock geochemical variations along the traverse are best exemplified by SiO_2, which increases from about 62–72% (Figure 8.33), with very tightly bunched contours. At the same time, all other major oxides except K_2O decrease significantly, as do most trace elements except Rb which increases significantly. Most notable are the changes in isotopic ratios determined by Halliday *et al.* (1980) and Halliday (1984), with initial $^{87}Sr/^{86}Sr$ ranging from 0.7052 to 0.7073, ϵNd ranging from -0.6 to -3.1, and $\delta^{18}O$ ranging from 8.5 to 11.9‰ (all expressed as variations from outer to inner facies).

The varieties of outer granodiorite fit all the criteria for I-type granites (Chappell and White, 1974), including the presence of hornblende, metaluminous bulk compositions, and appropriate levels of the Sr, Nd and oxygen isotope ratios. The inner BM granites, however, depart from the I-type classification and have strong affinities with the S-types in most important respects, especially their peraluminous compositions and evolved isotopic compositions, including values of $\delta^{18}O$ well above 10‰. These granites are not unequivocally S-types, but nor are they I-types and are perhaps best described as transitional S-types.

The I-type to S-type zonation in a fairly regular concentric structure is unusual and its origin is not well understood. The outer I-type granodiorites are generally similar to I-types worldwide and have an origin dominantly in a relatively juvenile lower crust. The S-type characteristics of the most evolved inner granites can be correlated with the local Silurian greywackes, and it is likely that these have melted to provide the innermost magmas, although this must have happened at considerable depth given that there is no evidence for local melting. How these two melting events led to an organized zoned pluton is not clear; Stephens (1992) has suggested that the control was rheological, but it is possible that the inner pulse hybridized with the outer to

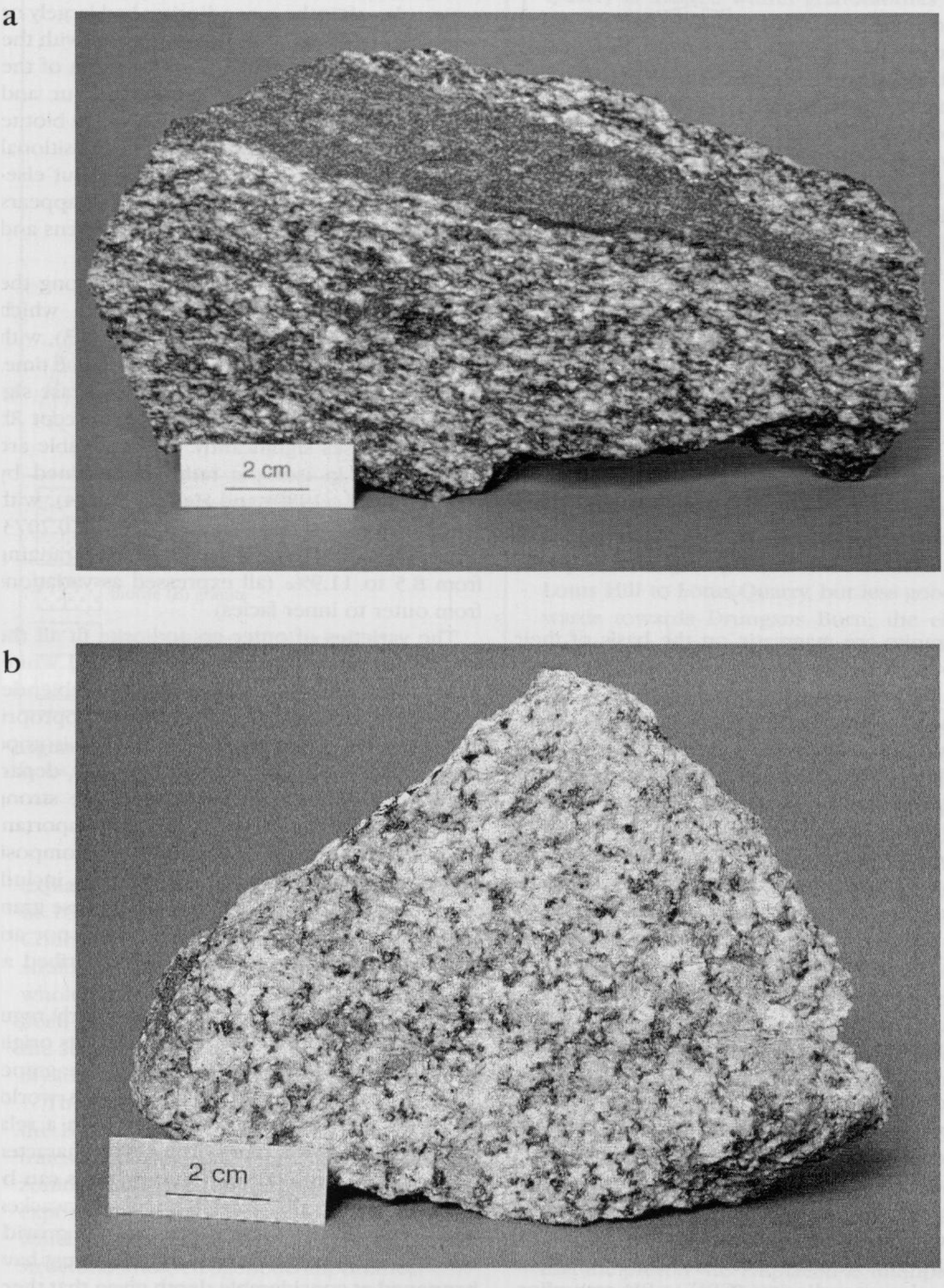


Figure 8.34 (a) Typical clinopyroxene-biotite-hornblende granodiorite, with enclave from the margin of the Criffel pluton. (b) Biotite-muscovite granite from the interior of the Criffel pluton. (Photos: W.E. Stephens.)

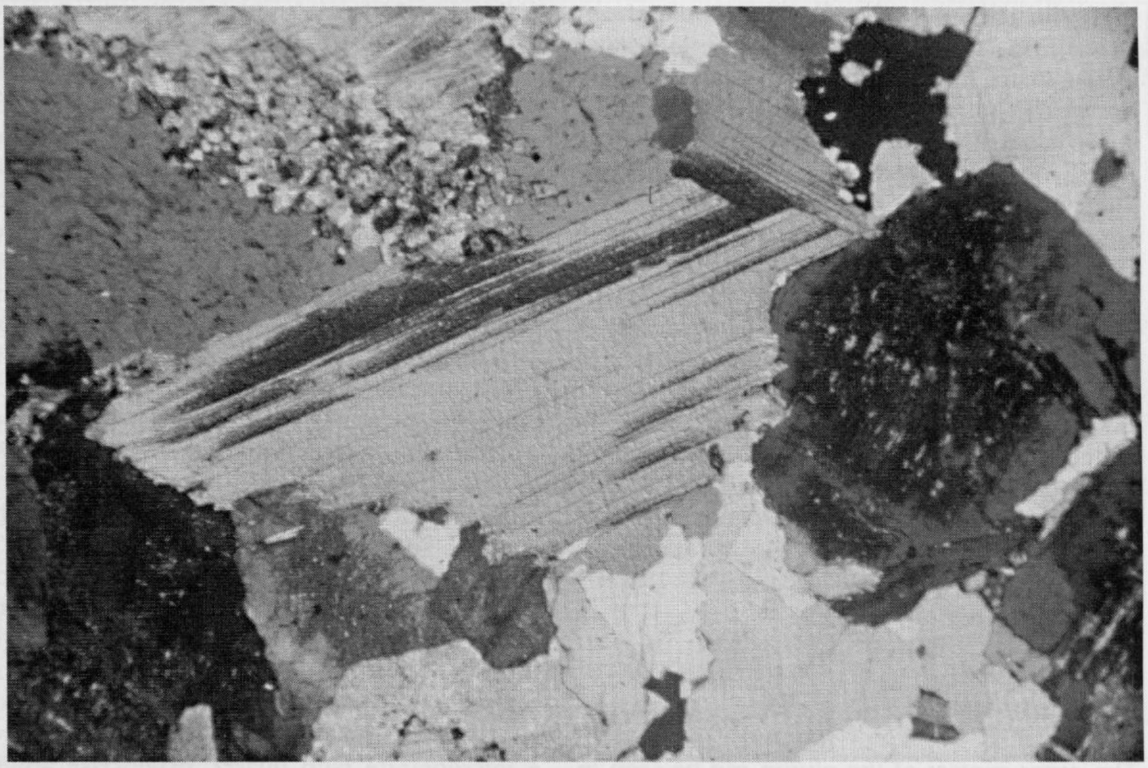


Figure 8.35 Photomicrograph of the biotite-muscovite granite from the Criffel pluton. (Photo: W.E. Stephens.)

produce the intermediate zones, although this would seem to be precluded by the fact that the outer granodiorites were largely crystallized when the granites were intruded (Courrioux, 1987).

Conclusions

The notion that originally homogeneous magmas differentiate to form diverse rock types is central to igneous petrology, and the products take many forms. In granites, such differentiation often takes the form of a zoned pluton, of which the Criffel pluton represents one unusual variety (I-type to S-type) which requires multiple pulses of magma derived dominantly from different sources (protoliths). The Lotus Hill to Drungans traverse is of international importance in this context. It provides a compact summary of this type of zonation and has contributed to detailed published studies of the observed variations as well as to some of the first discussions of the likely causes of such zonation. The contrasts in isotopic ratios between the zones make it especially likely that this pluton will be important in generating and testing new models for such zonation.

MILLOUR AND AIRDRIE HILL (NX 950 595)

W. E. Stephens

Introduction

The outcrops around Millour and Airdrie Hill (Figure 8.36), some 2–3 km south of the summit of Criffel, provide very good exposures of the outer contact and marginal zones of the Criffel pluton. A general introduction to the pluton and a discussion of the zoning is given in the Lotus Quarries to Drungans Burn GCR site description.

The marginal clinopyroxene-biotite-hornblende granodiorite facies contains abundant titanite and shows all the geochemical and isotopic characteristics of I-type granites (Stephens *et al.*, 1985). Features thought to be indicative of diapirism, including sharp contacts, steeply outward-dipping host rocks, mineral and enclave foliations with similar trends to the host rocks, and flattened enclaves, are well displayed. The evidence used in the stoping versus diapiric emplacement controversy (Phillips, 1956; Phillips *et al.*, 1981, 1983; Holder, 1983; Courrioux, 1987) can be examined here, as can many of the petrological features associated with the least evolved facies of the zoned pluton.

This site has been selected for the quality of the exposures and the range of features contained within a relatively small and accessible area. In particular, the site has among the best examples of discoidal enclaves in the UK, rivalling those of the classic Ardara pluton in Donegal (Pitcher and Berger, 1972; Holder, 1983; Pitcher, 1993).

Description

The outer contact of the pluton can be seen in the Kirkbean Burn in the SE corner of the site. The Silurian greywackes in contact with the granodiorites dip south-eastwards away from the contact at 50–60°. The contact may be traced along the break of slope in a south-westerly direction. The NE–SW strike of these contact rocks is more-or-less parallel to the regional strike but elsewhere, along the NE and SW contacts of the pluton, the regional strike is deflected into parallelism with the contact. For this reason, Phillips (1956) argued that the structures in the aureole are at least in part due to the emplacement of the pluton, and that the magma was emplaced forcefully (Phillips *et al.*, 1981). Veins of granitic material, rather more acidic than the local granodiorite, locally intrude along planar structures in the greywackes. These greywackes are recrystallized as a result of contact metamorphism, with significant growth of new biotite.

On the south and SE slopes of Millour and Airdrie Hill the clinopyroxene-hornblende-biotite granodiorite (Figure 8.34a) has a strong foliation, contains abundant mafic-rich enclaves (i.e. dark xenolithic inclusions) and is cut by microgranodiorite and microgranite dykes, and veins of aplite and pegmatite. The granodiorite consists of hornblende, commonly with cores of clinopyroxene, together with biotite and zoned plagioclase feldspar (andesine–oligoclase), some alkali feldspar and quartz. Titanite, zircon and apatite are the principal accessory minerals with some opaque minerals. The enclaves have the same mineralogy as the host granodiorites, but the mafic phases and plagioclase are more abundant. Country rock xenoliths can be seen on the southern slopes of Millour, close to the outer contact (i.e. near the break of slope), and these are aligned within the main foliation in the granodiorites. They decrease in number and size away from the contact and few are found beyond 100 m into the pluton.

Late stage veins of aplite are fairly common, usually just a few centimetres thick and whitish in colour, reflecting their dominant quartz and feldspar mineralogy. They cut across the enclaves and the main foliation in the granodiorites, but in places they show a deformation that is approximately parallel to the fabric in the host. Some pegmatites may also be found in these outcrops. Also present are dykes of 'porphyrite', a microgranodiorite with hornblende and/or plagioclase phenocrysts, and 'porphyry', a microgranite with quartz, plagioclase and/or biotite phenocrysts. These dykes are typically 20 cm to 1 m wide and trend approximately NW–SE towards the central granite.

The key feature of this site is the very strong foliation apparent in the granodiorite. This takes the form of a strong alignment of mafic enclaves combined with a parallel mineral alignment in the host. The enclaves appear as dark pod-shaped masses, typically 10 cm to 1 m in maximum length and disc-shaped in three dimensions. Measurements of the enclave dimensions by Courrioux (1987) show that the maximum:minimum length ratio varies from about 4 up to 20, indicating considerable deformation if the enclaves were initially equidimensional. The strong mineral foliation in the host rock is due to the alignment of feldspars, amphiboles and biotites. In thin section this is seen to be accompanied by strong deformation, with mortar texture of small quartz grains around large plagioclase crystals (protoclastic texture), bent plagioclase crystals and kinked biotites. These features indicate that the granodiorite suffered a high degree of deformation and, as all the quartz is seen to be deformed, the strain was taken up largely in the solid state. The foliation dips outwards at 45–65° to the SE or SSE, bracketing the dip of the country rocks.

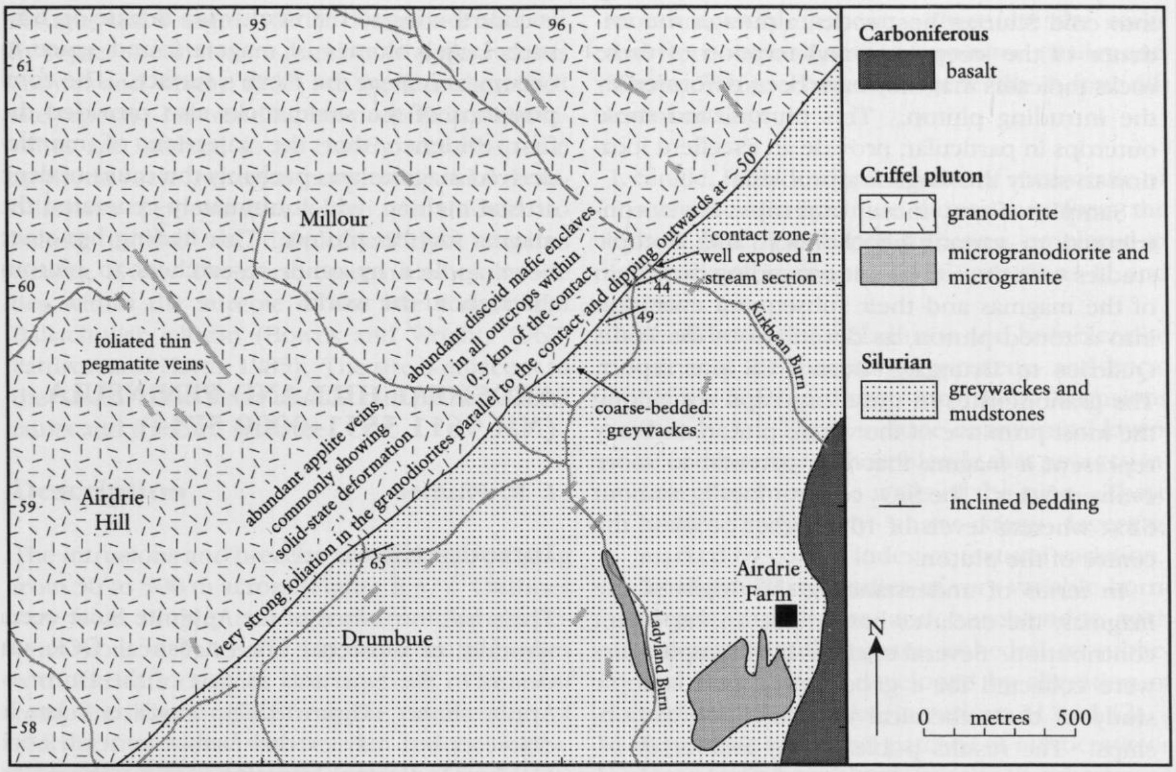


Figure 8.36 Map of the area around the Millour and Airdrie Hill GCR site, Criffel pluton, based on Phillips (1956), BGS 1:50 000 Sheet 5E (Dalbeattie) (1993) and observations by W.E. Stephens.

Interpretation

The field observations described above accord closely with the classic features of pluton emplacement by diapirism (i.e. magmas forcing their way into high levels of the crust by deforming their host rocks). The emplacement of granitic plutons is currently the subject of much debate, in particular concerning the role of diapirism at high crustal levels (Hutton, 1988a; Paterson *et al.*, 1996; Petford, 1996). The present view is that diapirism needs heat to be effective; deformation of hot plastic rocks by magmas may be possible but it is mechanically impossible to deform cold brittle rocks in the same way. Thus, according to many authors, diapirism is confined to the hotter middle crust and is not appropriate to the emplacement of granites at a high crustal level. The evidence for the emplacement of at least part of the Criffel pluton by diapirism is compelling, yet several features place it in the mesozonal category of plutons emplaced within the upper crust. It was intruded at the end of Silurian time but was already unroofed and providing material to form local arkose deposits in the Late Devonian.

There is a partial reconciliation of this problem in the work of Courrioux (1987). Phillips (1956) and Phillips *et al.* (1981, 1983) argued that the alignment and increasingly discoidal form of the enclaves away from the pluton margin is the result of convective flow. However, Holder (1983) and Courrioux (1987) suggested that the flattening is a consequence of ballooning of the magma during emplacement. The enclaves therefore provide evidence of the distribution of strain over the magma body during emplacement. An increase in strain within the granodiorites towards the internal boundary with the granites was interpreted by Courrioux as the effect of the emplacement of the inner granite magma pulse on the outer, largely consolidated granodiorite. At this time the outer granodiorite envelope would certainly have been at a high temperature and thus potentially capable of being deformed by an intruding magma. It is less easy to reconcile the emplacement of the first granodiorite pulse by diaprism into cold Silurian host rocks, although the evidence of the steepening and rotation of these rocks indicates that they have been deformed by the intruding pluton. This pluton, and these outcrops in particular, provide an excellent location to study this lingering problem.

Samples from these outcrops have contributed to various geochemical and isotopic studies with the aim of understanding the origin of the magmas and their subsequent evolution into a zoned pluton, as described in the Lotus Quarries to Drungans Burn GCR site report. The granodiorites in these outcrops are among the most primitive of the whole pluton and may represent a magma that was parental to more evolved facies. The SiO_2 content locally is about 62%, whereas levels of 10% higher occur in the centre of the pluton.

In terms of understanding the origin of the magmas, the enclaves have made an important contribution. Several enclave–host sample pairs were collected for a geochemical and isotopic study of their chemical equilibration relationships. The results published by Holden *et al.* (1987), Holden *et al.* (1991) and Stephens *et al.* (1991) indicate that considerable disequilibrium is recorded in these enclaves. The enclaves are invariably more primitive and mantle-like in their Nd isotopic signatures than the host (ϵNd of *c.* –2 for the granodiorite, compared with ϵNd of *c.* 0 for the enclaves), indicating that their residence time in the main magma was limited to less than that at which full equilibrium would be achieved for all elements and isotopes. These authors provided the first firm indication that such enclaves may be the partially equilibrated remains of mantle-derived basic magmas that intruded the crust, bringing heat to assist the melting of deep crustal rocks to generate granodioritic magmas. This is not the only interpretation of the data, and the enclaves could represent exotic magmas mingled at the emplacement level, although there is no independent evidence for this at Criffel, or that they represent disequilibrium fragments of restite.

Conclusions

The Millour and Airdrie Hill GCR site exhibits, in a small area, all the main features of the early granodiorites of the Criffel pluton, which are of international importance. The structures preserved have allowed a partial reconstruction of the emplacement history of the pluton and this is contributing to the worldwide debate on how such large volumes of magma found space to occupy very near the Earth's surface. The compositions of the same rocks also provided the first evidence that the injection of mantle-derived magmas was probably the cause of deep crustal melting, which ultimately generated the magma for this pluton. This finding has since been applied by other researchers to plutons throughout the world.

ARDSHEAL HILL AND PENINSULA (NM 9611 5551–0000 5734)

I. M. Platten

Introduction

The small intrusions of the Appinite Suite occur typically in clusters. The Ardsheal GCR site occurs in the type area as part of the Duror of Appin cluster (Figure 8.37), which is 8 km in diameter but may extend farther beneath Loch Linnhe. Individual intrusions are numbered on Figure 8.37 to facilitate reference in the text. The Ardsheal Hill and Peninsula area was described initially by Bailey and Maufe (1916), Walker (1927) and Bailey (1960). The area was remapped by Bowes and Wright (1961, 1967) and McArthur (1971) who recorded 20 significant intrusions and breccia pipes. Petrological work has been presented by Bowes and McArthur (1976), Bowes *et al.* (1964), Hamidullah (1983), Hamidullah and Bowes (1987), Wright and Bowes (1979) and Platten (1991). Local copper mineralization was reported by Rice and Davies (1979) to be spatially related to the intrusions (intrusion 5). Parts of the cluster outside the site have also attracted attention. The well-known Kentallen intrusion (intrusion 1) is at the NE end of the cluster (see the Kentallen GCR site report) and aspects of the southern part of the cluster, particularly some breccia pipes, were documented by Platten (1982, 1984). The site is far more accessible than any of the other appinitic clusters in Scotland and is frequently visited by undergraduate and other field courses.

The country rocks are quartzites, metalimestones, phyllites and slates of the Dalradian, Appin Group that have been metamorphosed to greenschist facies before emplacement of the appinitic intrusions (Bowes and Wright, 1967;

Treagus and Treagus, 1971). The area is also cut by representatives of a number of dyke swarms (Bowes and Wright, 1967; see the Kentallen GCR site report). NE-trending lamprophyric microdiorites are inferred to be closely related to the appinitic rocks, whereas porphyritic microgranodiorites ('porphyrites') are considered to belong to the late Caledonian dyke swarms (Bailey, 1960). The north-eastern end of the site lies within the aureole of the late Caledonian Ballachulish pluton (Bowes and Wright, 1967; Pattison and Harte, 1985). The site is adjacent to the Great Glen Fault and is cut by associated faults and fracture systems.

Description

The intrusions and breccias are all small, ranging from 50 to 500 m across (Figure 8.37). Outlines vary from simple, near circular or oval shapes (intrusions 4, 5, 15 and 16), to irregular bodies with intricate outlines (intrusion 8). The most complex shapes result from the intersection of dioritic intrusions with earlier breccia pipes. Exposed contacts between intrusions and breccias and with the external country rocks are generally steep, hence the inferred pipe form. No evidence of upward closure has been found. Intrusions may penetrate locally between the clasts in the breccias, but generally the contacts are sharp.

The main igneous rock type is a pyroxene-bearing mesocratic diorite or monzodiorite with variable amounts of biotite (intrusions 2–8, 14 and 16) (Hamidullah and Bowes, 1987). The pyroxene is augite/salite, occurring either as large, 2–8 mm crystals, giving the rock a porphyritic aspect or as small grains of less than 1.0 mm. Orthopyroxene is absent or very rare; olivine is present as a minor component. Hornblende may occur as overgrowths on the pyroxenes or as co-existing elongate prisms. A porphyritic chilled facies of these diorites with pyroxene phenocrysts in a fine groundmass occurs in intrusions 8 and 14. However, chilled margins are commonly localized or completely absent, with coarse-grained rocks occurring at the contacts in spite of the small size of the intrusions.

Hornblende diorites with conspicuous euhedral, elongate or equant, prisms of pargasitic hornblende are a distinctive and diagnostic feature of the suite throughout the Scottish Caledonides. Small calcite-filled vugs are a common accessory element. These are the rocks that were originally called 'appinites' (Bailey and Maufe, 1916). They occur generally in four different settings.

1. Single, fairly uniform bodies of mesocratic or melanocratic appinitic diorite may form the bulk of a pipe-shaped intrusion, emplaced in breccia or in country rock (intrusions 11 and 15).
2. Small bodies of meladiorite and hornblendite occur at the margins of pyroxene- and hornblende-bearing diorite intrusions (intrusions 8 and 13). These include near-vertical layers of comb-textured hornblende that point to in-situ growth on the walls of the pipe. These bodies commonly show steep layering, marked by colour index or textural variation.
3. Small (< 20 m) bodies of very variable hornblende meladiorite and hornblendite with characteristically equant, euhedral to subhedral hornblendes developed by alteration of earlier dioritic rocks (intrusions 11 and 12).
4. Pegmatitic veins and patches of mesocratic or leucocratic hornblende diorite may be found in all of the three above situations.

Leucocratic hornblende and pyroxene quartz-diorites and monzonites, and biotite and hornblende granodiorites are present. Small druses and minor sulphides are not uncommon in these rocks. Some form discrete bodies with only minor amounts of dioritic or mafic material at their margins (intrusion 18). They also occur as pipes, dykes, patches and veins in the other igneous rocks (intrusions 5, 8 and 14). Some granodiorite dykes penetrate the country rocks for a short distance (intrusions 14 and 18).

Small bodies of melanocratic or ultramafic rock are a common regional feature of the Appinite Suite. At the Ardsheal GCR site, biotite pyroxenite and biotite peridotite are common as small bodies at the margins of pyroxene diorite intrusions (intrusion 14). Thin (1–20 mm) anorthosite layers occur at the inner margins of these ultramafic bodies (Figure 8.38a) and within the main pyroxene diorite intrusions (intrusion 14). Hornblendite and meladiorite occur as small bodies at the margins of both hornblende diorite and pyroxene diorite intrusions (intrusions 3 and 8).

The intrusions have narrow (40–100 m) contact metamorphic aureoles (Platten, 1982) showing fine-grained, flinty hornfels with cordierite

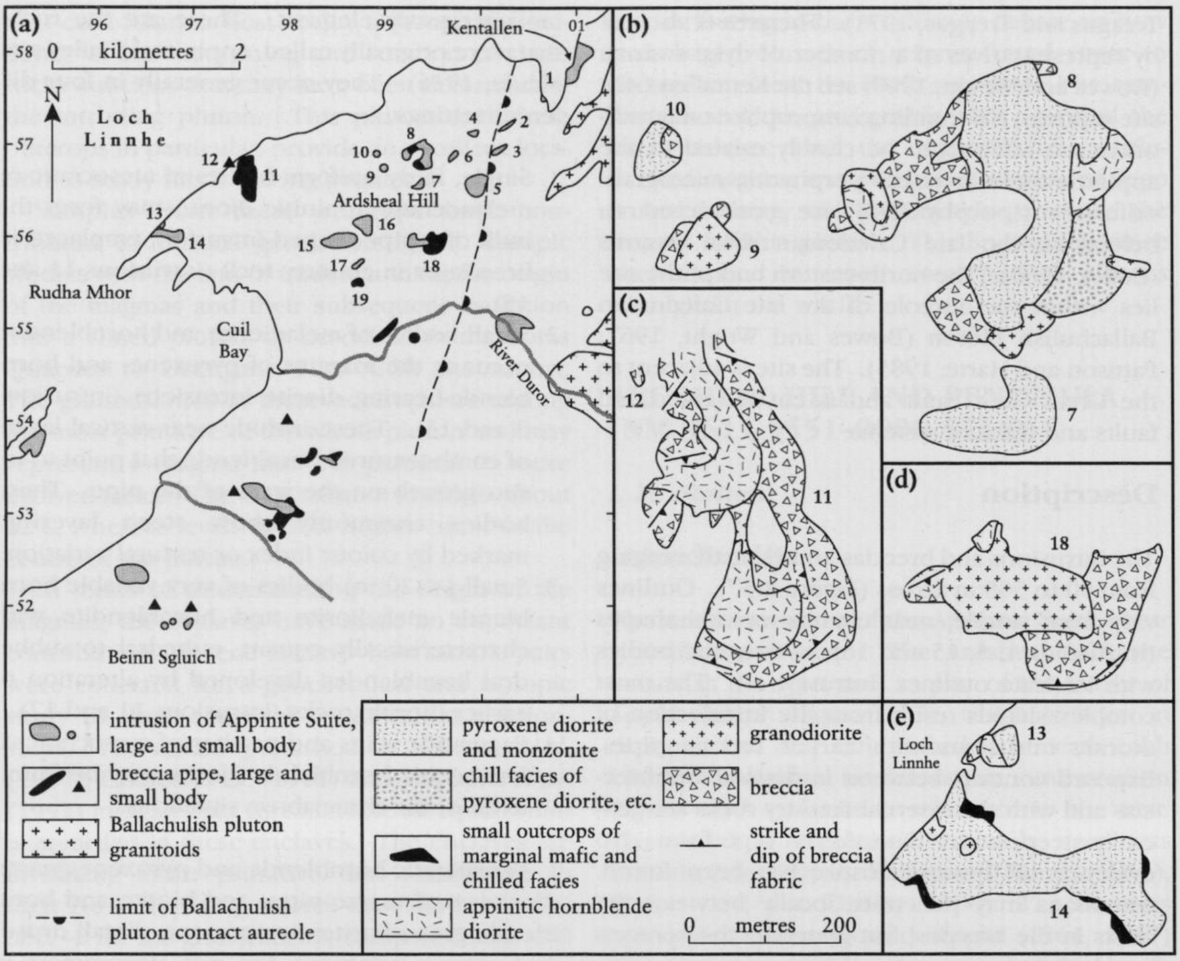
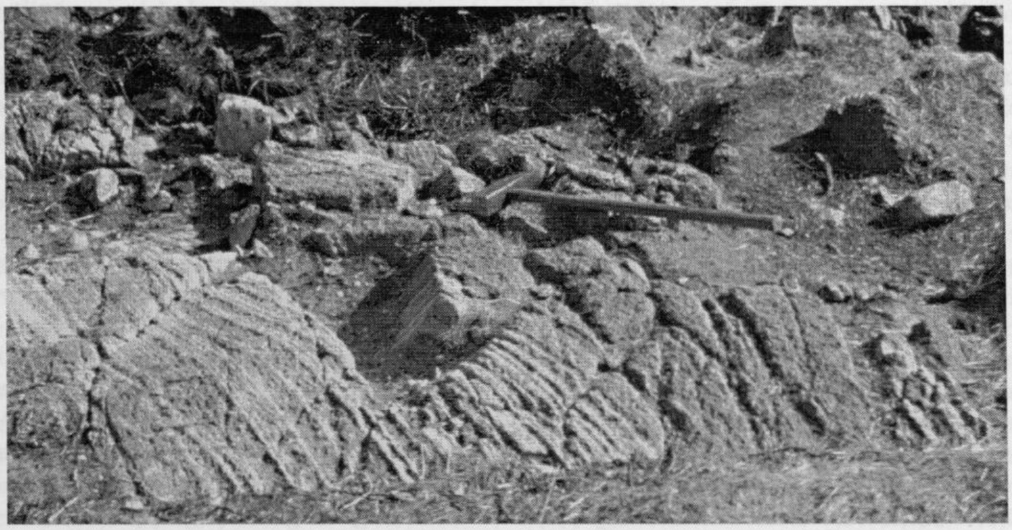


Figure 8.37 (a) The distribution of appinitic intrusions and breccia pipes in the Duror of Appin cluster. Intrusions within the Ardsheal Hill and Peninsula GCR site are numbered for reference in the text. (b), (c), (d) and (e) Examples of outcrop patterns within the Duror of Appin cluster. The intrusion numbers correspond to those given in Figure 8.37a. Figures b, d and e are redrawn with minor modification from Bowes and Wright (1967).

spots in pelites (intrusions 15 and 18). Localized partial melting and mobilization has been noted in pelites and feldspathic quartzites within a few metres of contacts with intrusions 14 and 18 (Platten, 1982). In the northern intrusions (1, 2, 3 and 5), later contact metamorphic effects of the Ballachulish pluton obscure the contact metamorphism due to the appinitic rocks (see the GCR site report).

Breccia pipes and rare dykes are associated with the appinitic intrusions (Bowes and Wright, 1961, 1967; Platten, 1982, 1984). These are characteristically composed of local country rock fragments that show evidence of rotation and local transport. Clasts are generally angular and most lie in the size range 0.05–1.0 m; sand-sized material is usually absent. Rounded clasts, mostly of quartzite, do occur as a minor component in some breccias (intrusion 11). Internal divisions may be mapped within some breccia pipes based on variations in clast size, rounding and lithology (intrusions 8 and 11). Breccias with abundant plate-shaped fragments show planar fabrics defined by parallel orientation of clasts (intrusions 11 and 18). In breccias dominated by phyllite clasts, most of the clasts are deformed and show face to face contacts leaving little pore space (intrusions 8 and 18). Breccias dominated by quartzite clasts show less deformation of clasts and some trace of pre-cement pore space may remain. This has a drusy quartz filling with minor pyrite and a carbonate mineral.

a



b

Figure 8.38 (a) Wall-parallel, steeply dipping layering of meladiorite and anorthosite at the SW margin of intrusion 14, in the Duror of Appin cluster (see Figure 8.37). (Photo: I.M. Platten.) (b) Composite dyke, Back Settlement, Ardsheal. The dyke, which cuts intrusion 12 to the NE, dips steeply towards the observer, with breccia in the footwall and lamprophyric microdiorite in the hanging wall. Magma has penetrated between breccia clasts at the irregular contact. (Photo: D. Stephenson.)

Interpretation

Bowes and Wright (1961, 1967) interpreted the breccias as forming as the result of explosions, largely based on the extensive fracturing of the Dalradian host rocks and the deformation of the breccia fragments. However the diorite intrusions, breccias, contact hornfels and later dykes of microdiorite and porphyritic microgranodiorite are also fractured and cut by drusy quartz veins. The timing of fracturing is discussed in the Kentallen GCR site description in which it is shown that the extensive fracturing is a very late event and thus unrelated to breccia emplacement. The breccia pipes at Ardsheal are now interpreted as having formed by the mechanisms proposed by Platten and Money (1987) for the Cruachan Cruinn breccias, near Crianlarich. Country rock collapse occurred above intrusions of volatile rich magma from which a vapour phase had separated. This produced narrow columns of fractured country rock which were fluidized and slightly transported as the vapour phase vented to the surface. Deformation of the clasts is interpreted as a post-breccia compaction driven by gravitational loading from overlying breccia and hydraulic loading by adjacent magma.

Emplacement of pipe-shaped intrusions resulted from the collapse of the country rock between the breccia pipes into an underlying, locally differentiated and de-gassed, magma chamber. Some very small intrusions (6, 7, 9 and 10) may have resulted from the removal, either upwards or downwards, of the clastic fill of breccia pipes. The relatively coarse-grained nature of the intrusions in even the smallest pipes and the evidence of local partial melting of wall rocks points to an active circulation of magma, probably with throughput to the surface. The cumulate marginal mafic and ultramafic rocks and the anorthositic layered rocks crystallized *in situ* on the walls from the convecting dioritic magmas. The more uniform cores, occupied by dioritic or evolved granodiorite, crystallized after convection ceased. Variation in the effectiveness of venting volatiles to the surface controlled the ferromagnesian mineralogy, pyroxene marking an open system and hornblende a closed system. Evolved leucocratic rocks intruded into the diorites may reflect the continued presence of magma bodies at depth below hot, but crystalline, diorite intrusions or simple filter-pressing of the lower parts of the diorite. A return to breccia formation is only known at one site (intrusion 12) where a breccia dyke cuts intrusive rocks (Figure 8.38b).

Conclusions

This is the type area of the Appinite Suite. It illustrates the extreme range of rock types (ultramafic, intermediate and acid) present in these highly differentiated intrusions, including the hornblende meladiorites with conspicuous euhedral hornblendes that characterize the suite. The site also provides excellent examples of the breccia pipes that are widely associated with the suite.

Igneous activity began with the formation of breccia pipes above underlying, volatile-saturated basic magma bodies. Primitive and more-evolved magmas were then emplaced, both into the breccia pipes and the country rock. Convection within the magma led to the accumulation of crystals against the walls of the pipes, which changed the composition of the remaining magma (crystal fractionation) to produce varied rock types. If the pipes remained sealed, volatiles were trapped and hydrous minerals crystallized (e.g. hornblende). These 'closed system' conditions alternated with 'open system' conditions in which the pipes functioned as feeders to surface volcanoes. Volatiles were released, possibly by explosive eruptions, and non-hydrous minerals crystallized in the remaining magma (e.g. pyroxene). Subsequently the cluster was cut by the late Caledonian Ballachulish pluton.

KENTALLEN (NN 0091 5766–0135 5822)

I. M. Platten

Introduction

The Kentallen intrusion is a member of the Duror of Appin cluster of appinitic diorite intrusions (see the Ardsheal Hill and Peninsula GCR site report) and is the type locality of 'kentallenite', a melanocratic olivine monzonite with unusually high MgO (15%) and K_2O (2.5%). The rocks post-date deformation and metamorphism of the Dalradian country rocks but pre-date emplacement of the Ballachulish granite pluton (Bowes, 1962). The rock 'kentallenite' was described by Teall (1888, 1897) and its occurrence was described by Hill and Kynaston (1900), Bailey and Maufe (1916) and Bailey (1960). More recently the field relationships have been described by Bowes (1962), Bowes and Wright (1967) and Platten (1966) and the petrology by Westoll (1968), Wright and Bowes (1979) and Hamidullah and Bowes (1987). The area lies within the aureole of the Ballachulish pluton which has been described by Pattison and Harte (1985). The site was revisited for this review and new data were obtained about the Kentallen intrusion margin and the sequence of igneous, hydrothermal and structural events. The name 'kentallenite' has been formally replaced by olivine monzonite and should now only be used in the strictly local context.

Description

The Kentallen intrusion is about 0.6 × 0.3 km (Figure 8.39), typical of many of the Appinite Suite plugs. Short sections of near-vertical contact can be seen at two places and the general topographical relationships suggest that the entire northern contact must be steep. The northern and southern contacts are grossly discordant to the strike of the host rocks while the eastern margin is broadly concordant. The body is thus a steeply plunging pipe. The bulk of the observed intrusion is emplaced in semipelite and quartzite of the Appin Phyllite and Limestone Formation but the eastern margin is in contact with a dolomitic member. The intrusion exhibits a relatively uniform interior but varied marginal rocks and structures.

The interior of the intrusion is composed of a uniform melanocratic olivine monzonite ('kentallenite') (Figure 8.39) which is well exposed in the railway and road cuttings. The rock is composed of olivine, diopside, plagioclase, orthoclase, anorthoclase, phlogopite, magnetite and apatite. The olivine and diopside are coarse grained, most being 2–8 mm, but rare elongate olivine crystals may reach 20 mm. The crystals are euhedral to subhedral and are densely packed, approaching a grain-supported fabric. Plagioclase occurs as small interstitial tablets. Phlogopite crystals are large, 10 to 30 mm, and poikilitically enclose the plagioclase and mafic minerals. Alkali feldspar either overgrows plagioclase or forms poikilitic crystals. Rare examples of rootless veins and patches of coarse, leucocratic feldspar–biotite rock, superficially similar to the interstitial minerals of the olivine monzonite, are seen in displaced blocks on the coast. Xenoliths and enclaves are generally absent.

Changes occur in the main olivine monzonite towards the contacts. The phlogopite shows a marked decrease in grain size (from >10 mm to <1 mm) and a change from poikilitic to interstitial texture. The olivine is much less abundant and the large (>10 mm) olivine crystals are absent. Colour index is reduced and olivine and pyroxene crystals are well separated from each other. Some enclaves of a porphyritic facies with very fine-grained matrix are present locally, close to the outer margin. This finer-grained margin abuts directly against country rock in the east but in the north and south is separated from the country rocks by sheets of diverse, earlier contact facies rocks.

The early contact facies is best exposed on the coast just south of Sron Garbh (Figure 8.39). The earliest rock is a very fine-grained porphyritic 'kentallenite' with pyroxene and olivine phenocrysts in a very fine-grained matrix, the 'large lamprophyre body' of Bowes (1962). Traced south this shows a rapidly gradational, near-vertical contact with pyroxenite. The pyroxenite is a clinopyroxene-phlogopite-plagioclase rock that is coarser grained (5–10 mm pyroxene) than most other rocks in the intrusion. Olivine appears abruptly to the south and the rock becomes a phlogopite-clinopyroxene-bearing peridotite. The phlogopite crystals in these ultramafic rocks form a subpoikilitic framework and show evidence of cataclasis and kinking. This is succeeded southwards by pyroxene-olivine meladiorite and then the slightly chilled margin of the main 'kentallenite'. The meladiorite shows fine, millimetre-scale, vertical layering at and near the contact.

Two marginal intrusions are emplaced between the country rock and the early contact facies rocks in the Sron Garbh section. The first is a medium-grained pyroxene-hornblende-biotite diorite that carries conspicuous xenoliths of the Appin Quartzite. This diorite locally carries small numbers of pyroxene phenocrysts. The second is a pyroxene-biotite diorite with large (5 mm) pyroxenes that carries a rounded xenolith of chilled porphyritic 'kentallenite'.

The country rocks at the northern margin (Figures 8.39, 8.40 and 8.41) show a conspicuous antiform with an axial trace parallel to the contact. The fold style is concentric with multiple, angular hinges, local decollement planes, changes in profile along the fold axial surface and minor box folds. Domains of breccia consist of plate-like fragments of siliceous metasedimentary rock in a white microgranite matrix. Major and minor fold hinges show bedding-normal, wedge-shaped, gaping tensile fractures filled by microgranite. These veins are rootless. The southern limb of the antiform is the most disturbed with an extensive breccia of pelite and quartzite clasts. These breccias contain 4–8 mm-diameter altered pyroxenes, olivines and hornblendes similar to those found in the adjacent marginal intrusion.

Four dyke sets cut the Kentallen intrusion (Figure 8.39). Microdiorite dykes, Set Dk1, trending NNE and ENE and white feldsparphyric microgranodiorite dykes, Set Dk2, are cut by granite veins and show fine-grained biotite

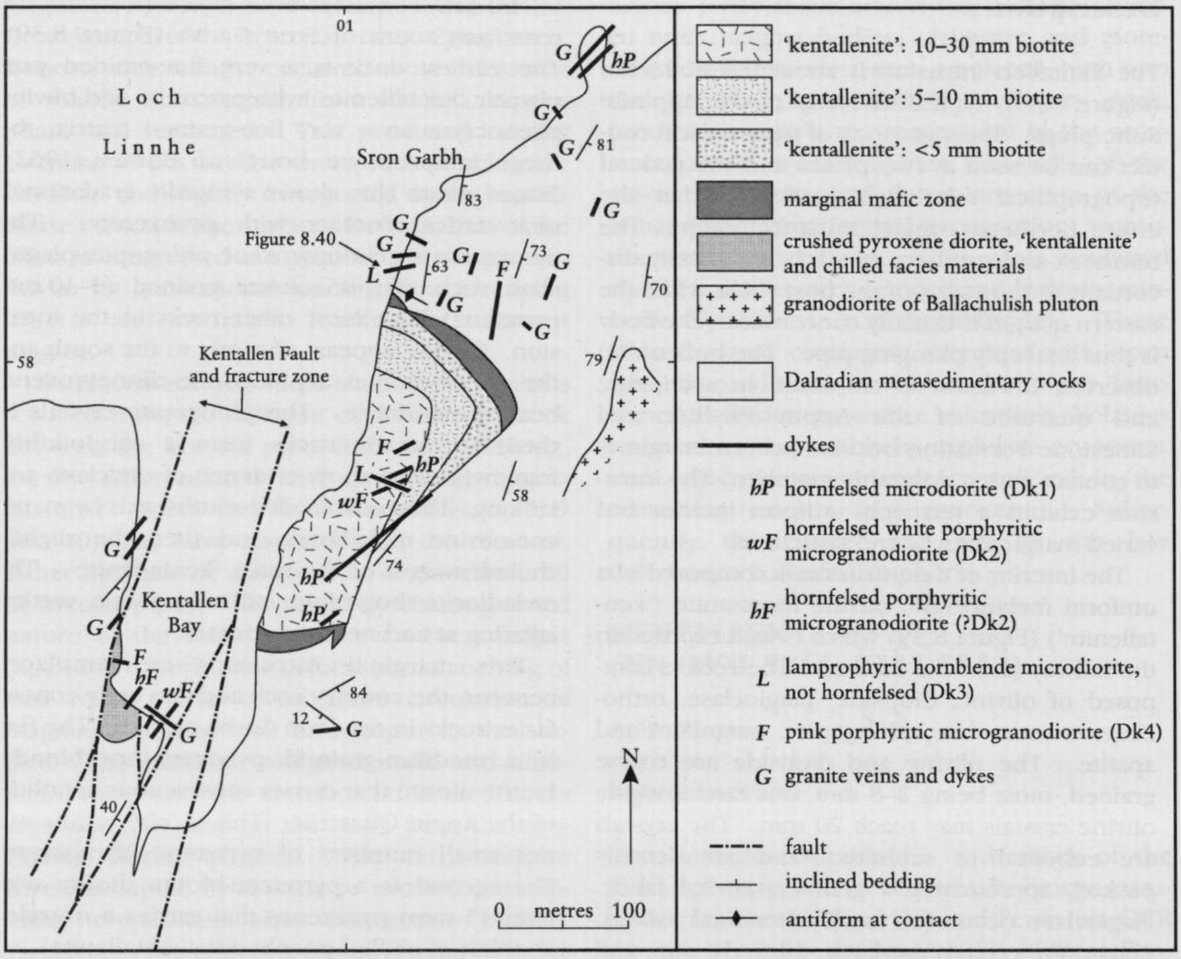


Figure 8.39 Map of the Kentallen appinitic intrusion.

and amphibole of hornfels origin in their matrix. An ENE-trending, hornblende microdiorite dyke, Set Dk3, with fresh, wholly igneous texture, cuts the hornfelsed microdiorites of Set Dk1 and one granite vein in the Sron Garbh section. A pink porphyritic microgranodiorite, Set Dk4, lacks secondary, hornfels-generated biotite and has a turbid altered appearance. It is cut by fracturing on the south side of Kentallen Bay that also affects the Kentallen intrusion. Relationships between Dk3 and Dk4 are not seen.

Four hydrothermal events have been recognized at Kentallen. (H1) Granular textured calcite veins occur as en echelon, concordant and discordant sheets in Dalradian rocks south of Sron Garbh. (H2) An early phase of hydrous alteration, with development of disseminated iron sulphides, is thought to have affected both the marginal rocks of the Kentallen intrusion and the early dykes of sets Dk1 and Dk2. These altered rocks have been extensively recrystallized by later contact metamorphism due to the Ballachulish pluton. (H3) The Kentallen intrusion contact in the Sron Garbh section is displaced by faults containing quartz veins. These lack an obvious drusy texture and contain <1% of pyrite and chalcopyrite. They are cut by granite veins and dykes of sets Dk3 and Dk4. (H4) The exposures on the south side of Kentallen Bay are cut by drusy-textured quartz-calcite-chalcopyrite veins associated with crushing and chlorite growth in the igneous rocks.

Two episodes of faulting are indicated at the site. NNE-trending faults lined with quartz (H3, above) cut the Kentallen intrusion and some Dk1 microdiorites in the Sron Garbh section. One is seen to be cut by a granite vein. These faults dip east at low to steep angles and have oblique-slip, normal and reversed movements. The second faulting event produced a sinistral offset of the margin of the Kentallen intrusion across Kentallen Bay (Figure 8.39) and some dextral and sinistral, oblique-slip, small faults dissecting the igneous rocks in the bay.

The Kentallen area lies within the inner aureole of the Ballachulish pluton (Pattison and Harte, 1985) and the northern part of the site shows good exposures of pelitic, semipelitic and calcareous hornfels. Calc-silicate rocks and granular calcite rocks are present, but poorly exposed, all along the eastern margin of the area. The pelitic rocks are coarse-grained cordierite hornfels with 2–10 mm poikiloblastic cordierite and local rootless veins of mobilized granitic material. Leucocratic biotite granodiorite dykes (trending NNE and ESE) with traces of yellow sulphides and lacking chilled margins cut the entire area. Contact metamorphic effects on fresh olivine monzonite are negligible, but hydrothermally altered igneous rocks develop contact metamorphic pyroxene, amphibole and biotite. The aureole obliterates most metamorphic effects associated with emplacement of the Kentallen intrusion.

Interpretation

The olivine monzonite ('kentallenite') is considered to be derived from magma represented by the porphyritic chill facies, which are similar to other chilled rocks in the Appinite Suite. Following the interpetation of similar rocks by Platten (1991), in-situ wall crystallization from a convecting magma formed the pyroxenite and peridotite cumulates of the marginal zones. Cataclasis of phlogopite in the pyroxenite and peridotite reflects the internal, gravitational deformation of these rocks while they formed weak layers with interstitial fluid that were only supported on one side. Temporary cessation of convection allowed crystallization of meladiorite at the walls. New, more mafic, magma was introduced into the pipe, displacing the existing magmas and triggering partial collapse and removal of the wall cumulates and initial chilled facies. This new magma quenched on the walls, trapping enclaves of penecontemporaneous fine-grained porphyritic rock and forming the relatively fine-grained outer facies of the main intrusion. Settlement and accumulation of olivine and pyroxene phenocrysts in the centre of the pipe led to the formation of the typical olivine monzonite ('kentallenite') with its densely packed olivine and pyroxene crystals. Compaction of this mass then expelled some interstitial residual liquid to form the leucocratic biotite monzonite segregations. The marginal intrusions at Sron Garbh may have been emplaced during collapse of the early contact facies rocks (Platten, 1983).

The time relationships of some events are reinterpreted here. The marginal fold at Sron Garbh is considered by Bowes and Wright (1967) to pre-date the Kentallen intrusion and to control its site of emplacement. The presence in the associated breccias of igneous material derived from the Kentallen intrusion and the rootless microgranite veins and patches in the fold hinges point to the fold forming in hot country rocks during emplacement of the Kentallen intrusion. The extensive fracturing south of Kentallen Bay was interpreted by Bowes and Wright (1967) as an important initial stage in the emplacement of the Kentallen intrusion. However, the recognition here that this fracturing affects the intrusion, and even later rocks, removes any link with emplacement. The fracturing is considered to be related to movements in the nearby Great Glen Fault-zone.

An extended sequence of late Caledonian magmatic, hydrothermal and structural events established at the site, can be summarized as follows.

1. Calcite veins (H1) are considered to pre-date the Kentallen intrusion; their texture results from contact metamorphism by the Ballachulish granite.
2. Kentallen intrusion emplaced in at least two stages and marginal fold formed.
3. Emplacement of Set Dk1 microdiorite and Set Dk2 leucocratic porphyritic microgranodiorite dykes.
4. Faulting and quartz vein emplacement (H3), post-dating microdiorite. Early Great Glen Fault movement.
5. Ballachulish granite emplacement and associated contact metamorphism of the products of events 1, 2 and 3 above.
6. Emplacement of Set Dk4 pink porphyritic microgranodiorite dykes.
7. Faulting, extensive shattering, chloritization and quartz-chalcopyrite-calcite vein emplacement (H4). The low temperature assemblages are considered to indicate that the frac-

Figure 8.40 Disharmonic minor folds at the margin of the Kentallen intrusion in the Sron Garbh section; view looking east. A 0.15 m-thick layer of quartzite on the left shows concentric folding (bottom) and fracture and pull-apart (top). A patch of breccia composed of 10 to 30 mm-long plates in a matrix of fine-grained microgranite occupies the space between differently folded adjacent layers (centre). A set Dk1 dyke cuts the structures at the top of the photograph.

tures post-date hornfelsing due to the Ballachulish granite. Late Great Glen Fault movement.

Certain events are only partly dated relative to this sequence. The extensive recrystallization of the Kentallen intrusion marginal zones and of the early Dk1 and Dk2 (event 3) dykes indicates that they had been reduced to a hydrous mineralogy that was unstable under prograde contact metamorphism during emplacement of the Ballachulish granite. This implied alteration (collectively termed H2) is most closely related in time to the emplacement of the Kentallen intrusion but is likely to post-date the main intrusive phases. It clearly pre-dates event 5 but time relationships with event 4 are unknown. Hornblende microdiorite dykes of Set Dk3 post-date event 5 but relationships with events 6 and 7 are unknown.

Conclusions

The Kentallen GCR site exposes a small intrusion of olivine monzonite, which is part of a large cluster of intrusions and breccia pipes in the type area of the Appinite Suite (see the Ardsheal Hill and Peninsula GCR site report). The olivine monzonite, which is unusually MgO and K_2O rich, is a distinctive lithology that was formerly termed 'kentallenite' after this, the type locality. The contact facies are particularly well exposed and the location, within the aureole of the Ballachulish pluton and close to the Great Glen Fault-zone, together with the wide range of igneous, hydrothermal and structural events that can be recognized, enable a complex sequence of time relationships to be determined.

The intrusion was emplaced in at least two stages, after the main deformation and metamorphism of the Dalradian country rocks,

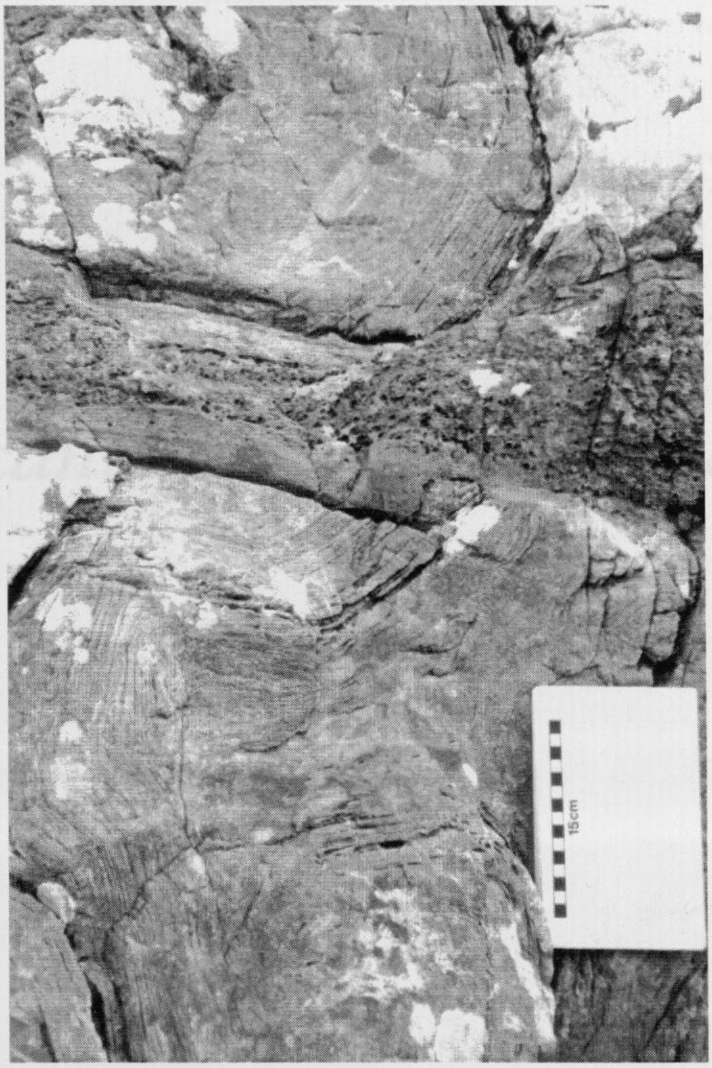


Figure 8.41 Microdiorite dyke of set Dk1 cutting minor folds at the northern margin of the Kentallen intrusion; view looking east. The dyke shows axial concentration of mafic phenocrysts. The folded layer shows radial granitic veins forming a fan around the hinge (top). Traced downwards, this layer forms a box fold with few veins, but its core (centre) is mobilized and the bedding has been destroyed. The mobilized area forms a detachment surface isolating another fold closure (beside the scale), which shows an irregular mass of granite veins in the hinge and abrupt truncation of bedding on the upper limb. (Photos: I.M. Platten.)

but prior to two sets of dykes, hydrothermal alteration, early movement on the Great Glen Fault and subsequent emplacement of the Ballachulish pluton. This was followed by the intrusion of two further sets of dykes, extensive shattering, hydrothermal alteration and veining and later movements on the Great Glen Fault.