BONAWE TO CADDERLIE BURN

A. J. Highton

OS Grid Reference: NN008336–NN038385

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 km^2, 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).

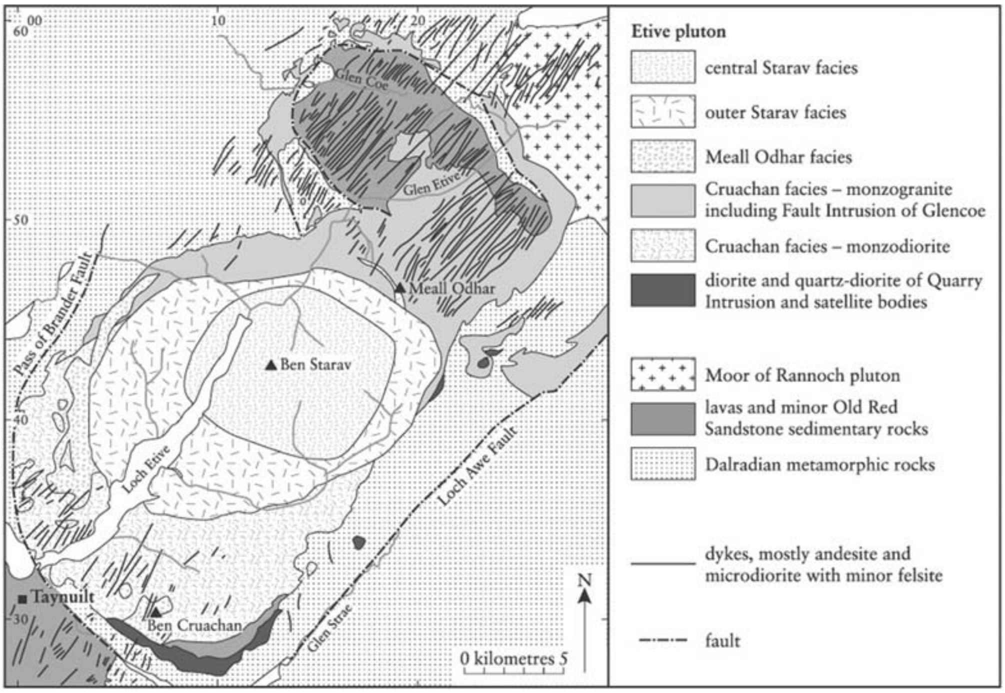

Figure 8.15: Map of the Etive and Glencoe complexes, after Anderson (1937) and Batchelor (1987).

An accompanying NE-trending swarm of synplutonic 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.

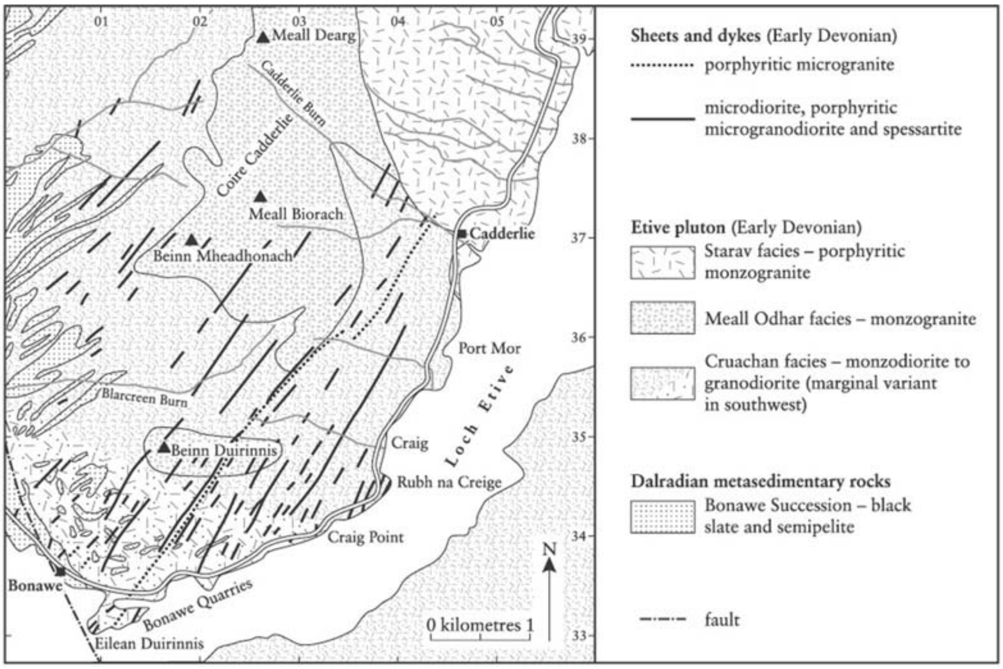

Figure 8.16: Map of the area around the Bonawe to Cadderlie Burn GCR site, Etive pluton, adapted from BGS 1:50 000 Sheet 45W.

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 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 (Figure8.17). 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.

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.)

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.

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).

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