BEN NEVIS AND ALLT A'MHUILINN

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Introduction

The international importance of this GCR site is that it is a well-exposed Caledonian post-tectonic granitic intrusion, around 425 Ma old, within which is preserved a sequence of volcanic rocks. The presence of the volcanic rocks warrants inclusion of the site in this chapter, but the plutonic rocks are important representatives of the Argyll and Northern Highlands Suite described in Chapter 8.

Ben Nevis is Britain's highest mountain; its summit and spectacular north-facing cliffs (Figure 9.7) are part of a down-faulted block (*c*. 2.5 km in diameter) of volcanic and sedimentary rocks that subsided along an encircling ring fracture during a caldera-forming eruption. All traces of the surface caldera and the accompanying volcanic rocks have been removed by erosion, but the deeper structural feature (i.e. the cauldron subsidence) remains. The down-faulted block is completely surrounded by a granitic intrusion (the Inner Granite), which is in turn partly surrounded by an earlier granitic intrusion (the Outer Granite).

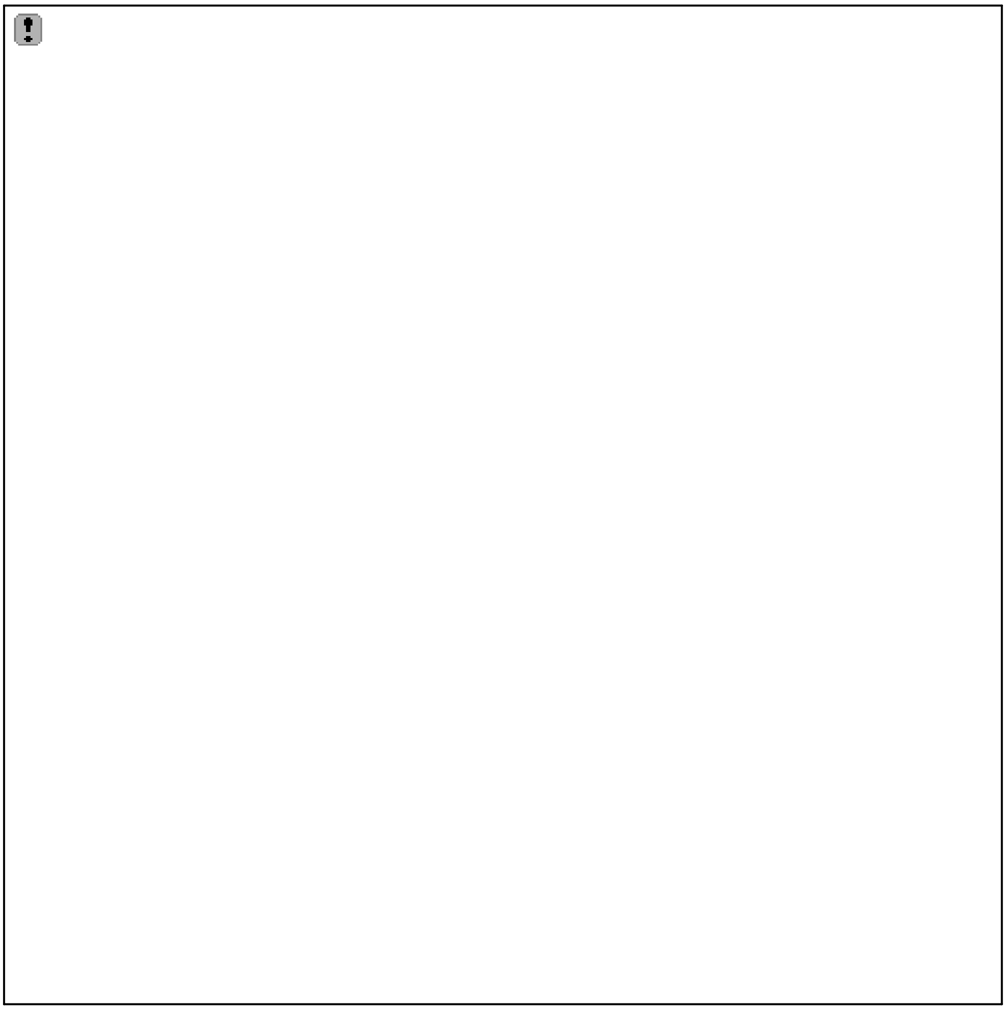

Figure 9.7: View up the Allt a'Mhuilinn towards Coire Leis, showing the volcanic rocks of the downfaulted block (cliffs of Ben Nevis on the right), and the Inner Granite (low-lying ground on the left and the backwall of the coire in the distance. (Photomosaic: BGS nos. C 1794 and 1795.)

Geochemical relationships reveal a complex story of magma evolution involving interactions between different batches of magma and various petrogenetic processes (i.e. mantle melting, fractional crystallization, and crustal melting).

The GCR site includes terrain within 2 km of the summit of Ben Nevis, plus a narrow strip along the Allt a'Mhuilinn, which flows NW from the northern corrie, Coire Leis, giving a section across the plutonic units.

Description

The Ben Nevis igneous complex (*c*. 42 km²) is dominated by granitic rocks, with volcanic rocks restricted to an elliptical outcrop in the south (*c*. 3.5 km²). Early workers (Maufe, 1910; Bailey and Maufe, 1916) recognized three principal lithologies: (1) Outer Granite, (2) Inner Granite, and (3) a down-faulted block dominated by volcanic rocks. They noted that the Inner Granite is a homogeneous intrusion, whereas the Outer Granite consists of four distinct intrusive sub-units. Later workers (Anderson, 1935b; Haslam, 1965; Burt, 1994) remapped the contacts between the four Outer Granite sub-units. This description follows the work of Burt (1994), which is encapsulated in Figure 9.6.

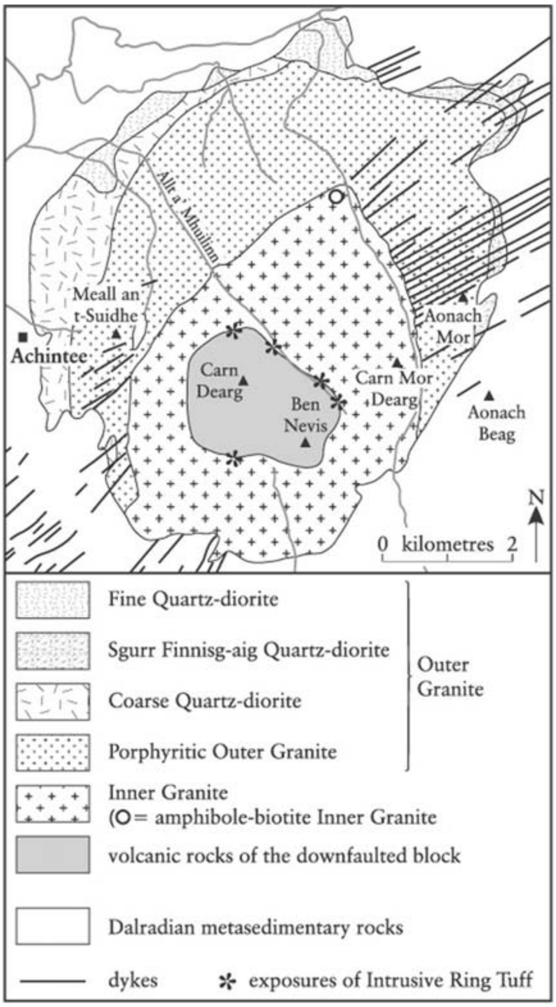

Figure 9.6: Map showing units comprising the Ben Nevis igneous complex. Note the Inner Granite (essentially a ring intrusion) completely surrounding the down-faulted block. The contact between the two is where the rhyolite and 'flinty crush-rock' (i.e. an ancient vent) is found. The Outer Granite consists of four distinct (and mappable) subunits, emplaced in a margin-to-core sequence. Note also that the dyke-swarm cuts through all subunits of the Outer Granite that lie in its path, but does not penetrate the Inner Granite or the downfaulted block. After Bailey (1960), Burt (1994) and Burt and Brown (1997).

The Ben Nevis granitic rocks are intruded into various garnet-grade Dalradian metasedimentary rocks, which generally strike NE–SW:

(youngest)
Ballachulish Slate (Ballachulish Subgroup)
Ballachulish Limestone (Ballachulish Subgroup)
Leven Schist (Lochaber Subgroup)
undifferentiated rocks of the Grampian Group
(oldest)

To the SE the granitic rocks cut the Fort William Slide which generally forms the junction between Grampian Group rocks and younger lithologies. This ‘coincidental' association between a Siluro-Devonian volcano-plutonic complex and a major ductile slide is also evident at Glen Coe.

The Outer Granite

The Outer Granite has steep external contacts with the surrounding metasedimentary rocks (Maufe, 1910; Anderson, 1935b). The contact is usually sharp, but in the east there are zones showing considerable brecciation and veining. Veins from a few millimetres to several metres in width penetrate the metasedimentary rocks up to 100 m from the contact, while brecciation is confined to discrete zones within 20 m of the contact. The breccia matrix is granitic, and metasedimentary blocks within the breccia have moved only a few metres (Burt, 1994).

Burt (1994) noted that each of the four units of the Outer Granite (see Table 9.1) are themselves composed of multiple pulses of magma. This is more evident in the earlier units, where more rapid cooling has preserved boundaries between pulses. Later units that cooled more slowly (e.g. the Porphyritic Outer Granite) show considerable mingling between the pulses of magma.

All four units of the Outer Granite are cut by a prominent NE–SW dyke-swarm, which is particularly intense in the east. The average width of the dykes is 3 m (Anderson, 1935b), and Bailey (1960) reported that they vary in composition from *c*. 58 to 75% SiO_2. In complete contrast, the dyke-swarm does not cut the Inner Granite, yet the Inner Granite can be observed cutting five dykes that intrude the adjacent Outer Granite (Maufe, 1910; Bailey, 1960).

The Inner Granite

The Inner Granite is a notably fine-grained granitic rock that is unusually rich in plagioclase, and this led Bailey (1960) to classify it as a ‘trondhjemite' (= leucotonalite). The ring of Inner Granite has contacts with three different lithologies – outer contacts (steep and inclined outwards) with Dalradian rocks and the Outer Granite, and an inner contact (also steep and inclined outwards) encircling the down-faulted block (Maufe, 1910; Bailey, 1960; Burt, 1994).

In places, at the contact between the Inner Granite and the down-faulted block, there is an unusual fine-grained, pinkish to dark-grey rhyolite with contact-parallel flow-banding. Within this rhyolite is a ‘flinty crush-rock' very similar to that at Glen Coe (see the Stob Mhic Mhartuin GCR site report). Burt and Brown (1997) described this rhyolite in detail, noting that the best exposure is along the Allt a' Mhuilinn *c*. 250 m upstream of the climbing hut. The rhyolite contains abundant euhedral phenocrysts of plagioclase (up to 2 mm), plus some biotite, amphibole, and rare quartz. Rare xenoliths (rounded and less than 1 cm) include examples of Dalradian rocks, dacitic lava, and unmetamorphosed sedimentary rocks, all of which can be correlated with lithologies that occur within the down-faulted block. Rhyolite veins (from 1 to 40 cm in width) penetrate the down-faulted block for up to 500 m from the contact.

The down-faulted block

The down-faulted block is approximately 2.5 km in diameter and is surrounded on all sides by the Inner Granite. It has a basin-like structure, with the margins markedly buckled upwards

(Maufe, 1910; Bailey, 1960). Burt (1994) has divided the down-faulted block into four distinct volcaniclastic formations (Table 9.2), which rest on Dalradian metasedimentary ‘basement'. The exposed thickness is approximately 650 m.

Three broad trends are evident: (1) the persistence of subaqueous conditions throughout the sequence; (2) the absence of volcaniclastic material in the early deposits, which contrasts with the dominance of such material in later deposits; (3) lateral thickness variations in all four formations.

Interpretation

Field relationships indicate an age sequence from Outer Granite to down-faulted block (i.e. volcanic activity) to Inner Granite. The prominent NE–SW dyke-swarm (which only cuts the Outer Granite) provides two important pieces of information: (1) that the regional stress field involved local dilation along a NW–SE axis; and (2) that the dykes were injected before intrusion of the Inner Granite. Although the dykes do not cut the down-faulted block, this may simply be a consequence of the down-faulted block descending from a level in the crust that did not favour dyke injection. However, it does indicate that dyke injection took place *before* subsidence of the down-faulted block, and it is conceivable that dyke injection was contemporaneous with the development of volcanism at Ben Nevis.

The variable nature of the Outer Granite has been commented upon by all workers (Maufe, 1910; Anderson, 1935b; Bailey, 1960; Haslam, 1968; Burt, 1994), who all recognized four mappable units within the discontinuous ring (although each drew slightly different boundaries between the units). Burt (1994) argued that the Outer Granite units were emplaced into the crust in a ‘forceful ballooning style of intrusion' and that in places intrusion was accompanied by explosive release of volatiles, with the development of intrusion breccias. The preservation of internal contacts within each unit suggests that each consists of a number of separate pulses. These contacts are better preserved in the earlier units (e.g. the Fine Quartz-diorite) suggesting more rapid cooling in early units relative to later units. The margin-to-core sequence of intrusion partly explains this, with early pulses encountering ‘cold' Dalradian crust and later pulses encountering either pre-warmed crust or still hot earlier granitic magma. Anderson's (1935b) observations that the Outer Granite becomes more silicic with height (*c*. 1200 m of vertical exposure) is interesting, as this might be a relict of an original magma chamber stratification that existed prior to final cooling and solidification. This point has not been fully addressed by later workers and requires re-assessment.

The Inner Granite has steep, outward-dipping inner and outer contacts (Maufe, 1910; Burt, 1994), and appears to have been intruded in a passive (permitted) manner (Burt, 1994). It varies in composition from 67.9 to 71.9% SiO_2 which suggests that it might be the remnants of a zoned magma body.

The sedimentary rocks preserved in the down-faulted block appear to be similar to modern-day playa lake deposits and indicate that a freshwater lake existed (and persisted) at Ben Nevis. It is likely that a small sedimentary basin existed (or that the Ben Nevis basin was part of a larger structure), in which flash floods were a persistent feature in the warm and arid climate of the time (Burt, 1994). Early non-volcaniclastic sediments gradually became replaced by volcaniclastic sediments and by proximal volcanic rocks. The presence of Dalradian clasts in debris flows suggests that there was considerable relief in the area (Burt, 1994 estimates at least 300 m of relief), and there is good evidence of active erosion after emplacement of the various volcanic and sedimentary formations. It is notable that no volcanic rocks more evolved than andesites are found *in situ* – although ‘exotic' clasts of dacite and rhyolite do occur, which may have come from neighbouring volcanic centres.

The down-faulted block indicates that substantial subsidence occurred (well over 650 m), and the upturned margins of the block suggest that there was frictional dragging as the block subsided (Maufe, 1910; Bailey, 1960). This conflicts with observations (and published cross sections) showing that the contact is outward-dipping, and further work is needed to resolve this paradox. (It is possible that inward-dipping ring faults are characteristic of near-surface environments, and that these become vertical and then outward-dipping at depth.) Subsidence was probably accompanied by venting of magma to the surface, and the fine-grained rhyolite at the junction of the down-faulted block and Inner Granite is interpreted by Burt and Brown (1997) as the remains of an ignimbrite conduit formed during caldera collapse. As such it is comparable to features developed in the Glencoe ring intrusion (see the Stob Mhic Mhartuin GCR site report) and it has been named the ‘Ben Nevis Intrusive Ring Tuff' by Burt and Brown.

Large-scale subsidence along encircling ring fractures at evolved silicic centres is generally accompanied by pyroclastic eruptions at the surface (cf. Druitt and Sparks, 1984), and it appears that Ben Nevis supported an evolved magma system that vented to the surface during a cataclysmic eruption (Burt, 1994; Burt and Brown, 1997). It should be stressed that only the early products of the Ben Nevis volcano are preserved in the down-faulted block; later volcanic rocks (which may have included syncaldera dacites and rhyolites) have all been removed by erosion.

One of Burt's (1994) major contributions is a comprehensive geochemical survey of the igneous complex. The following points summarize his main findings.

1. Ben Nevis is a typical Argyll and Northern Highlands Suite calc-alkaline igneous complex.

2. High-K, calc-alkaline compositions of all igneous rocks (with some volcanic rocks being mildly alkaline).

3. Inner Granite and Outer Granite lie on separate geochemical trends, suggesting two distinct phases of intrusive activity; the Ben Nevis Intrusive Ring Tuff has geochemical similarities to a locally preserved amphibole-biotite granite marginal phase of the Inner Granite (Burt and Brown, 1997).

4. Volcanic rocks (andesite, dacite and rhyolite) spent little time in subsurface magma chamber(s) prior to their eruption.

5. Andesite compositions cluster between 63 and 67% SiO_2.

6. Early andesites show the largest amount of contamination with crustal rocks; later andesites are relatively uncontaminated (inferred from Nd and Sr isotope systematics).

7. Plutonic rocks reached the upper crust (*c*. 1 kb depth).

8. Trace element geochemistry indicates a major role for amphibole fractionation at depth (for all magmas).

9. Plagioclase fractionation largely controlled the geochemical evolution of magmas once they were emplaced in the upper crust.

10. Strong temporal trend of magma system, generating variable early compositions and more homogeneous later compositions.

11. Appinite intrusion may be intimately related to the development of the igneous complex (i.e. appinites pre-, syn- and post-date the Coarse Quartz-diorite).

Incorporating these findings with the field evidence, Burt (1994) provided a synthesis of the magmatic evolution of Ben Nevis as follows.

1. Initiation of melting in SW Highland light rare-earth element (LREE)-enriched mantle.

2. Early magmas contaminated by interaction with lower crust and influenced by processes of assimilation and fractional crystallization; periodic intrusion of magmas to mid-crustal magma chamber(s); some early andesites and granitic rocks probably reached upper crust direct from lower crust without residing in mid-crustal magma chamber.

3. Fractional crystallization in developing mid-crustal magma chamber(s), with assimilation of Dalradian metasedimentary rocks.

4. Establishment of upper crustal magma chamber(s) where fractional crystallization became dominant, accompanied by localized contamination (by upper crustal Dalradian

metasedimentary rocks) of chamber magmas and the magmatic conduits leading to the surface; these upper crustal magmas later solidified to form the various granitic rocks (which are believed to be the source rocks for much of the indigenous volcanic rocks within the down-faulted block).

Conclusions

At Ben Nevis the highest ground is occupied by volcanic rocks that sunk hundreds of metres into an underlying body of still-molten magma. This subsidence was accompanied by the eruption of magma to the surface through an encircling ring fracture. Erosion has removed all trace of the volcanic depression (caldera) that would have been created during this major subsidence event (cauldron subsidence), and the deposits of the accompanying eruption (pyroclastic flows). The volcanic rocks are preserved only because of large-scale subsidence of a down-faulted block, and provide compelling evidence that some of the igneous complexes associated with the Caledonian Orogeny reached high levels in the crust and supported flourishing volcanic superstructures. The international scientific importance of Ben Nevis is that it provides access to levels within an ancient igneous complex where relationships between volcanic rocks (erupted on the land surface), subvolcanic rocks (emplaced just beneath the surface), and plutonic rocks (emplaced deeper beneath the surface), can be investigated and interpreted.

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