Caledonian Igneous Rocks of Great Britain

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Chapter 4

Lake District and northern England

INTRODUCTION

D. Millward

In Ordovician times the Lake District and northern England formed part of the microcontinent of Eastern Avalonia, that comprised southern Britain and adjacent parts of continental Europe. Faunal and palaeomagnetic evidence show that in the early Ordovician, Eastern Avalonia was attached to the supercontinent of Gondwana in a high southern latitude. Avalonia–Gondwana was separated from Laurentia to the north by the Iapetus Ocean (Figure 2.1). Avalonia then rifted from the supercontinent in the mid-Ordovician, drifted northwards during closure of the Iapetus and eventually collided with Laurentia in tropical latitudes during the Silurian. The line of closure of the ocean now lies beneath the Solway Firth (Figure 4.1).

During the Palaeozoic, from Late Cambrian to early Llanvirn times, deep-marine turbidites of the Skiddaw Group were deposited on the passive margin of Eastern Avalonia (Cooper *et al.*, 1995). Regional uplift from this non-volcanic, deep oceanic environment to a subaerial one was the prelude to volcanism. Subsequently, two episodes of intense igneous activity occurred in the Lake District. Firstly, during the Ordovician (Llandeilo–Ashgill), basaltic, andesitic and rhyolitic lavas and voluminous pyroclastic rocks were erupted at the continental margin of Avalonia, above a subduction zone in which the Iapetus Ocean was being consumed (Fitton *et al.*, 1982). The Eycott Volcanic Group (EVG) and the Borrowdale Volcanic Group (BVG) represent two contemporaneous volcanic fields (Figure 4.2). This phase of magmatism culminated in the emplacement of much of the Lake District granitic batholith (Hughes *et al.*, 1996). Secondly, in late Silurian to Early Devonian times, additional granitic plutons were emplaced in the Lake District and northern England subsequent to the closure of the Iapetus.

The volcanoes were subaerial (Branney, 1988a), of low relief and probably located within extensional basins, a feature illustrated by the single marine incursion in the upper BVG. The earliest known terrestrial trace fossils in the world occur in volcaniclastic sedimentary rocks from the BVG (Johnson *et al.*, 1996). The oldest

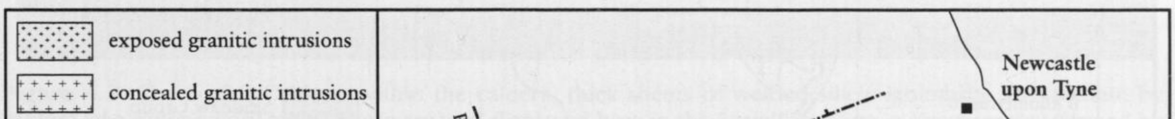


Figure 4.1 Lower Palaeozoic inliers of northern England and locations of the major, buried batholiths. Exposed granitic intrusions: En, Ennerdale; Es, Eskdale; Sh, Shap; Sk, Skiddaw; Th, Threlkeld; D Dufton.

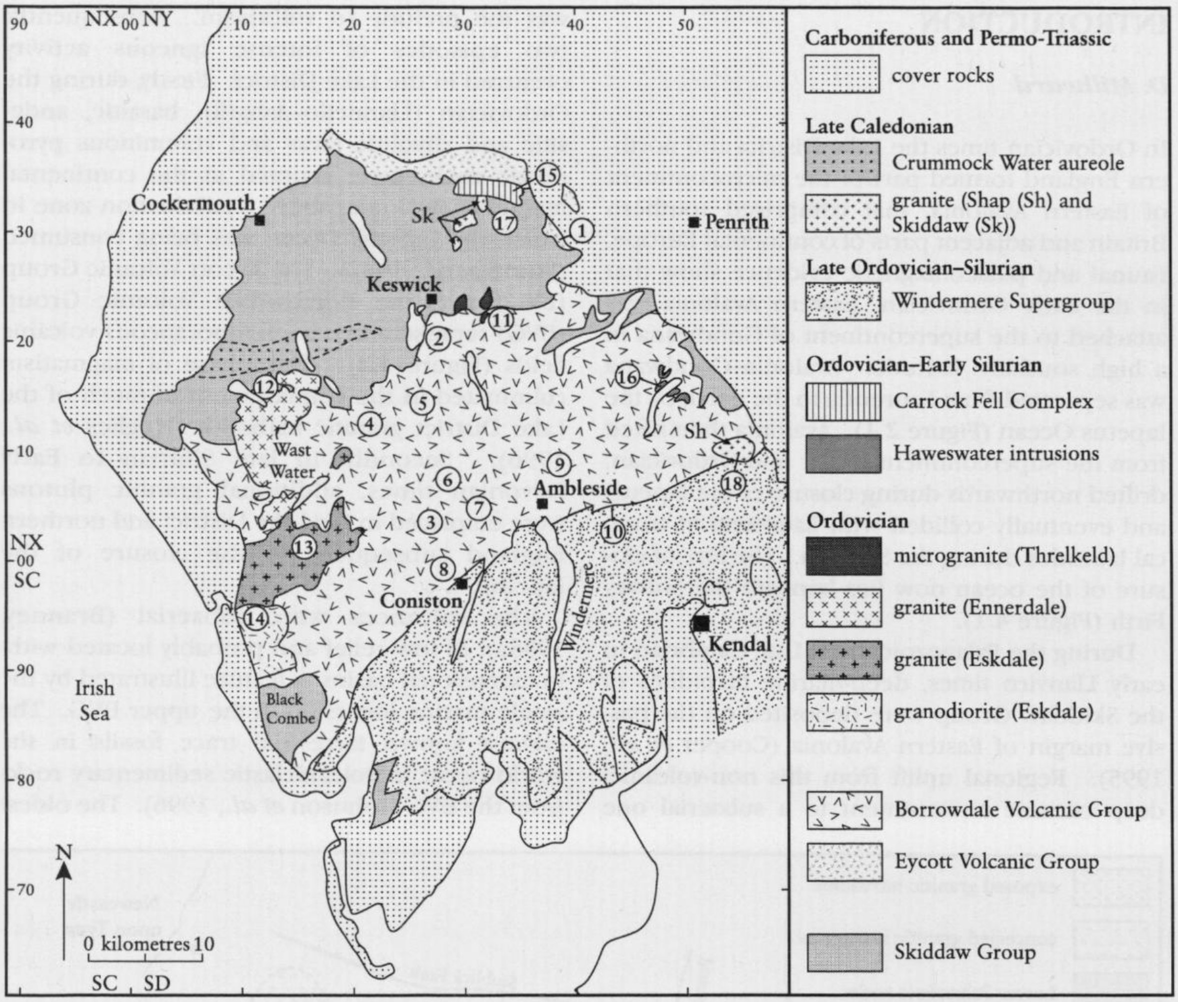


Figure 4.2 Lower Palaeozoic geology of the Lake District inlier showing the location of the GCR sites. 1, Eycott Hill; 2, Falcon Crags; 3, Ray Crag and Crinkle Crags; 4, Sour Milk Gill; 5, Rosthwaite Fell; 6, Langdale Pikes; 7, Side Pike; 8, Coniston; 9, Pets Quarry; 10, Stockdale Beck, Longsleddale; 11, Bramcrag Quarry; 12, Bowness Knott; 13, Beckfoot Quarry; 14, Waberthwaite Quarry; 15, Carrock Fell; 16, Haweswater; 17, Grainsgill; 18, Shap Fell Crags.

record of volcanism is in the western Lake District where phreatomagmatic tuff cones were eroded and redeposited. The main part of the lower BVG is dominated by andesite block lavas that built up sub-horizontal plateaux (Petterson *et al.*, 1992). The lavas emanated from many vent sites and pyroclastic deposits and volcanic mudflows locally filled valleys; unconsolidated volcaniclastic deposits were reworked by rivers and sheet floods. At the end of the effusive phase the terrain had a relative relief of no more than 110 m. Though of subtly different geochemical composition, the EVG had an evolution comparable to this lower part of the BVG.

A widespread voluminous andesitic ash-fall deposit heralded a major change to explosive volcanism that dominated the later part of the BVG episode. The succession of lavas, overlain by thick, ponded silicic ignimbrites and followed by lava domes and lacustrine sedimentary strata is typical of a caldera cycle (Branney and Soper, 1988). In the central Lake District the recently discovered Scafell Caldera contains a thick pyroclastic fill (Branney and Kokelaar, 1994a). Caldera collapse developed through incremental, piecemeal subsidence with many closely spaced faults. The waning stage of the collapse phase comprised small-volume pyroclastic flows

Figure 4.3 The Scafell Caldera: within the caldera, thick sheets of welded silicic ignimbrite are overlain by caldera-lake sedimentary rocks. These are well displayed here in the Scafell Syncline, a structure that formed by Early Devonian tectonic compression of the Ordovician downsag caldera. In the crags on the left of the skyline the rocks dip to the right, and on the right the lacustrine rocks exposed in the pointed peak of Bowfell dip to the left. The bedded rocks in the foreground are breccias avalanched from local volcanotectonic faults during caldera collapse. (Photo: BGS no. D4031.)

and lava domes and the broad depression that marked the site of the caldera was then filled with lake sediments. The low-relief crustal sag that resulted from caldera collapse following the paroxysmal eruption of voluminous pyroclastic flows is seen today tectonically tightened into the Scafell Syncline (Figure 4.3).

In the SW Lake District repeated cycles of pyroclastic eruptions and volcaniclastic sedimentation succeed the Scafell Caldera succession in the Duddon Basin, the volcanotectonic sag that was later deformed as the Ulpha Syncline (Millward *et al.*, in press). Calderas were probably formed, though the geometry of these is less well understood than in the Scafell Caldera. Also, regional subsidence and extensional faulting may have contributed to development of the basin and marine conditions were established for a short time. After the events of the Duddon Basin succession, fluvial and lacustrine sedimentation became widespread throughout the Lake District. Contemporaneous pyroclastic activity continued, producing ash-fall tuffs and generating sediment-gravity flows that contained juvenile material. Basaltic andesite and andesite sills were emplaced into unconsolidated, wet sediments. Further extensive silicic pyroclastic eruptions periodically interrupted the dominantly sedimentary regime.

As the Eycott and Borrowdale volcanic episodes waned, marine conditions became established across the eroded and thermally subsiding volcanic pile and lasted for more than 40 million years from late Ordovician to the Early

Devonian. The earliest Ashgill rocks are shallow marine and carbonate rich. Silicic volcanic eruptions occurred in the east of the Lake District and, in the SW, tuff-turbidites were deposited. A marked increase in subsidence and sedimentation rate during the Ludlow epoch has been associated with a foreland basin migrating southward across the Lake District during the final stages in the closure of the Iapetus Ocean (Kneller, 1991). This was initiated when the northern margin of Eastern Avalonia collided with the margin of Laurentia producing a flexural basin ahead of a SE-propagating thrust sequence (Kneller *et al.*, 1993a). Final inversion of the foreland basin and development of typical 'slate belt' structures, folds, cleavage and associated faults appears to have climaxed during the Acadian Event in the Early Devonian. Cleavage formation was synchronous with emplacement of the Early Devonian Shap and Skiddaw granites and associated dykes (Soper and Kneller, 1990).

The sequence of igneous events in the Lake District and northern England is summarized in Figure 4.4 and the sites selected to represent the magmatic evolution of this area are located on Figure 4.2.

Volcanic rocks in the Skiddaw Group

The Skiddaw Group contains few volcanic rocks. The middle part of the Llanvirn, Tarn Moor Formation comprises mudstone with up to 5% volcaniclastic beds, including bentonite and tuffaceous, turbiditic sandstone (Cooper *et al.*, 1995). Several igneous sheets in the succession, for many years regarded as lavas and considered to represent the earliest record of volcanism in the Lake District, were recently shown to be sills and probably related to the later, more substantial, subduction-related volcanic episodes described below (Hughes and Kokelaar, 1993).

Eycott Volcanic Group (EVG)

In the northern part of the Lower Palaeozoic inlier the Skiddaw Group is overlain unconformably by the EVG, comprising at least 3200 m of subaerial medium-K, continental margin, tholeiitic volcanic rocks (Cooper *et al.*, 1993). The succession comprises basaltic andesite, andesite and dacite lavas and sills along with interbedded tuff, lapilli-tuff and volcaniclastic sedimentary rocks. Massive intermediate and acidic lithic-rich and vitric lapilli-tuff comprise the uppermost 800 m of the group. The type section for the EVG is described in the Eycott Hill GCR site report, which also contains examples of the distinctive plagioclase-megaphyric basaltic andesite. Volcaniclastic sedimentary rocks at the base of the EVG contain a marine microflora indicating that the volcanic rocks are not older than late Llanvirn and possibly of Llandeilo –Caradoc age (Millward and Molyneux, 1992).

Borrowdale Volcanic Group (BVG)

The BVG forms the high fells of the central Lake District and occurs in the Cross Fell and Teesdale inliers (Figure 4.1). The succession comprises about 8 km of subaerial, calc-alkaline continental-margin lavas, sills, pyroclastic and volcaniclastic rocks associated with caldera development (Millward *et al.*, 1978; Branney and Soper, 1988). The rocks are unusual among volcanic suites worldwide because of the presence of almandine–pyrope garnet phenocrysts that occur in andesite, dacite and rhyolite (Fitton, 1972). The BVG is generally considered to be Llandeilo or early Caradoc (Wadge, 1978). The Holehouse Gill Formation, within the upper part of the BVG, is probably Caradoc (Harnagian–Soudleyan) on the basis of its marine microflora (Molyneux, 1988). The radiometric date of 457 ± 4 Ma for the BVG (Sm-Nd on garnet–whole-rock pairs; Thirlwall and Fitton, 1983) is compatible with the Caradoc biostratigraphical age.

Subaerial volcanic successions, such as the BVG, are rare in the geological record. Volcanic landforms, particularly those constructed with abundant pyroclastic deposits, are not generally preserved because of explosive disintegration, weathering and erosion; most are represented by volcaniclastic and tuffaceous sedimentary rocks within subaqueous sequences. However, the extensional tectonic regime and successive episodes of caldera collapse ensured preservation of the BVG. Many primary volcanic features are exquisitely preserved on the weather-worn exposures in the fells. The combination, therefore, of volcanic processes, tectonism, uplift and erosion during the last 450 Ma provides a unique insight into the deeper levels of, and processes that occur within, this type of volcanic province.

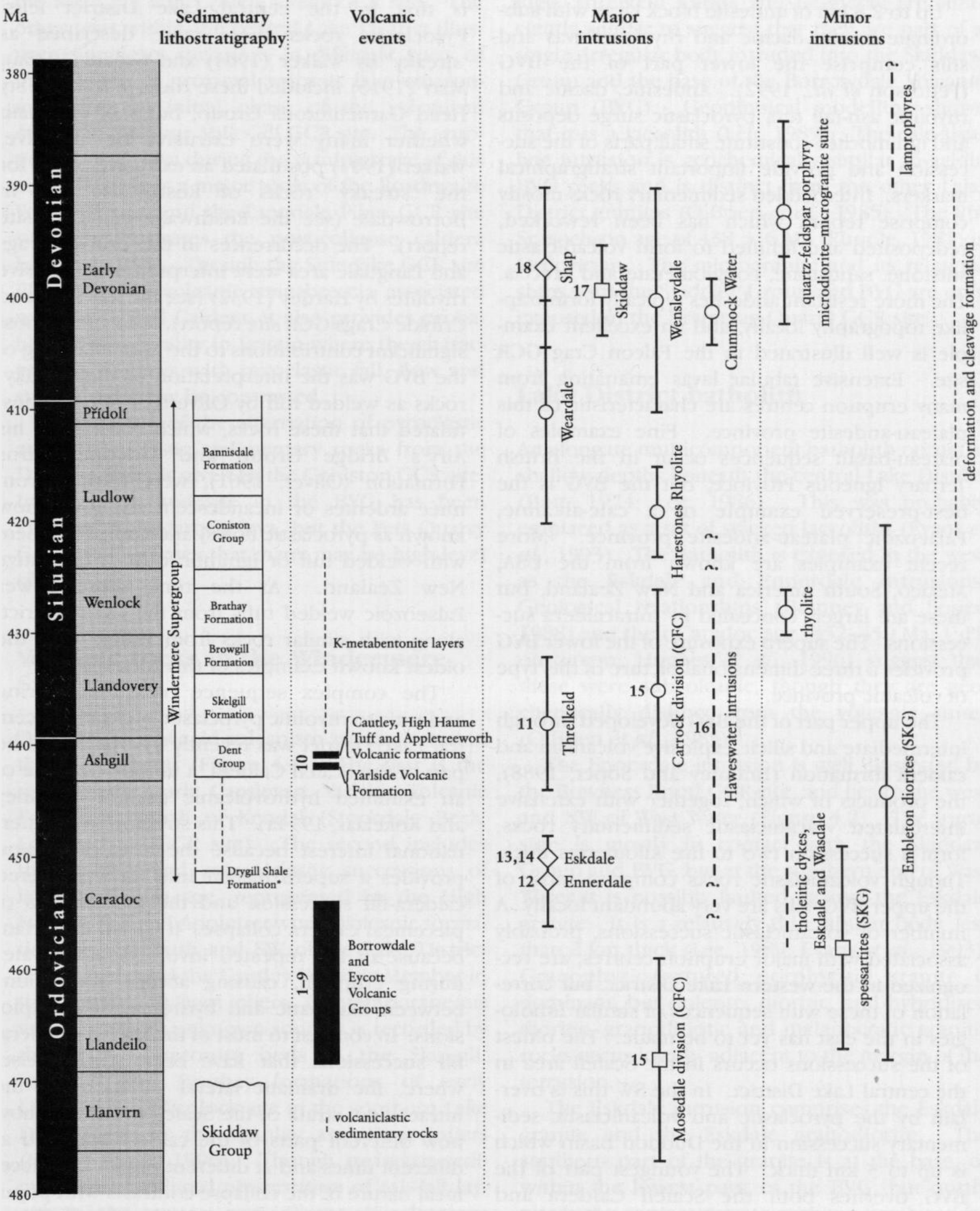


Figure 4.4 Summary chart of Lake District Caledonian igneous rocks. Bold numbers are GCR sites (numbers as per Figure 4.2). Radiometric dates: diamonds U-Pb; circles Rb-Sr; squares K-Ar; see text for sources. 1σ error bars are shown. Period of deformation and cleavage formation from Merriman *et al.* (1995). CFC Carrock Fell Complex; SKG Skiddaw Group.

*Note: In the northern Lake District the base of the Windermere Supergroup is at the base of the Drygill Shale Formation; in the central/southern Lake District the base of the supergroup coincides with the base of the Dent Group (Kneller *et al.*, 1994).

Up to 2.8 km of andesite block lavas with subordinate basalt, dacitic and rhyolitic lavas and sills comprise the lower part of the BVG (Petterson *et al.*, 1992). Andesitic, dacitic and rhyolitic ash-fall tuff, pyroclastic surge deposits and ignimbrites constitute small parts of the succession and provide important stratigraphical markers. Interbedded sedimentary rocks mostly comprise tephra which has been reworked, redeposited and lithified to form volcaniclastic siltstone, sandstone, conglomerate and breccia. The more resistant andesites typically form trap-like topography locally, and an excellent example is well illustrated in the Falcon Crag GCR site. Extensive tabular lavas emanating from many eruption centres are characteristic of this plateau-andesite province. Fine examples of plateau-basalt sequences occur in the British Tertiary Igneous Province, but the BVG is the best-preserved example of a calc-alkaline, Palaeozoic plateau-andesite province. More recent examples are known from the USA, Mexico, South America and New Zealand, but these are largely concealed by intracaldera successions. The superb exposure of the lower BVG provides a three-dimensional picture of this type of volcanic province.

The upper part of the BVG developed through intermediate and silicic explosive volcanism and caldera formation (Branney and Soper, 1988), the products of which, together with extensive intercalated volcaniclastic sedimentary rocks, form a succession two to five kilometres thick. Though volcaniclastic rocks comprise most of the upper BVG, sills are very abundant locally. A number of volcaniclastic successions, probably associated with major eruption centres, are recognized in the western Lake District, but correlation of these with sequences of similar lithologies in the east has yet to be made. The oldest of the successions occurs in the Scafell area in the central Lake District. In the SW this is overlain by the pyroclastic and volcaniclastic sedimentary succession in the Duddon Basin which is up to 3 km thick. The youngest part of the BVG overlies both the Scafell Caldera and Duddon Basin successions, and predominantly comprises volcaniclastic sedimentary rocks with intercalated thick ignimbrite sheets (Millward *et al.*, in press). A significant and dominantly andesitic welded ignimbrite succession is largely concealed beneath Permo-Triassic cover rocks in west Cumbria (Millward *et al.*, 1994).

The best known of the pyroclastic successions is that in the central Lake District fells. Pyroclastic rocks there were described as 'streaky' by Walker (1904) and Green (1915a). Marr (1916) included these rocks within his Sty Head Garnetiferous Group, but was uncertain whether many were extrusive or intrusive. Walker (1904) postulated an extrusive origin for the 'streaky' rocks of Rosthwaite Fell in Borrowdale (see the Rosthwaite Fell GCR site report). The occurrences in the Crinkle Crags and Langdale area were interpreted as intrusive rhyolites by Hartley (1932) (see the Ray Crag and Crinkle Crags GCR site report). One of the most significant contributions to the understanding of the BVG was the interpretation of the 'streaky' rocks as welded tuff by Oliver (1954). He postulated that these rocks, which constituted his Airy's Bridge Group and Lincomb Tarns Formation (Oliver, 1961), were formed from nuée ardentes or incandescent ash-flows (now known as pyroclastic flows) and compared them with welded tuff or ignimbrite from his native New Zealand. At the time these Lower Palaeozoic welded tuffs from the Lake District, along with similar rocks from Wales, were the oldest known examples of this rock type.

The complex sequence of garnet-bearing andesitic to rhyolitic pyroclastic rocks in the central Lake District was recently interpreted to be part of the Scafell Caldera, a unique example of an exhumed hydrovolcanic caldera (Branney and Kokelaar, 1994a). This structure is of international interest because the level of erosion provides a superb insight into its well-layered caldera-fill succession and the mechanisms of piecemeal caldera collapse. It is also important because of the repeated involvement of water during eruption, causing abrupt alternations between magmatic and hydromagmatic explosions. In contrast to most of the massive caldera-fill successions that have been studied elsewhere, the dramatic lateral variations in the intracaldera strata of the Scafell sequence show how different parts of the caldera subsided at different times and at different rates. The piecemeal nature of the collapse contrasts with popular models of simple, piston-like collapse (Lipman, 1984; c.f. Ben Nevis and Allt a' Mhuilinn and five Glencoe GCR sites, this volume).

The piecemeal caldera model with its layered silicic caldera-fill pyroclastic rocks, the progressive deformation of the welded tuffs and the formation of volcanotectonic faults is developed in the Ray Crag and Crinkle Crags GCR site. The other sites within the central Lake District illustrate significant variations in different parts of the caldera. A proximal volcanic lake environment for the initial phase of the volcanism occurs in the Sour Milk Gill GCR site. The eruption of silicic lava during the waning stage of this eruptive cycle is a major topic of the Rosthwaite Fell GCR site, and the Langdale Pikes GCR site superbly illustrates the post-collapse caldera lake succession. Though the Side Pike GCR site illustrates the volcanic megabreccia associated with the Scafell Caldera, it also provides probably the best locality in Britain where the characteristics of rocks with pyroclastic fall, flow and surge origin may be contrasted.

An example of the alternation of pyroclastic and volcaniclastic sedimentary rocks from the Duddon Basin is given by the Coniston GCR site. In the past, andesite in the BVG has been assumed to be largely lava, but the Pets Quarry GCR site illustrates that many may be high-level sills.

Volcanic rocks in the Windermere Supergroup

Two episodes of acid volcanism are preserved in the Dent Group (Figure 4.4). The first is the major silicic, early Cautleyan, Yarlside Volcanic Formation, north of Kendal (Stockdale Beck, Longsleddale GCR site). The second includes thin, widespread volcaniclastic successions of late Rawtheyan age, represented by the High Haume Tuff and Appletreeworth Volcanic formations in the south and SW of the Lake District respectively, and the Cautley Volcanic Member in the Cautley and Dent inliers. Contemporaneous volcanism from unknown sources is recorded by thin K-metabentonite beds in the Skelgill, Browgill and Brathay formations of early Llandovery to Wenlock age in the southern Lake District and in the Cautley and Dent inliers (Fortey *et al.*, 1996). Though turbidite sedimentation hindered preservation of ash-fall layers in the upper part of the Windermere Supergroup, early Ludlow K-metabentonites are recorded from the Ribblesdale (Craven) inlier (Figure 4.1; Romano and Spears, 1991).

Threlkeld intrusions

East of Keswick, microgranite outcrops on Low Rigg, Threlkeld Knotts and Bramcrag are sufficiently similar to suggest that they are part of a single, irregular body intruded into the Skiddaw Group and the base of the Borrowdale Volcanic Group (BVG). Geophysical modelling shows that it is a laccolith (Lee, 1989). The calc-alkaline intrusion is geochemically similar to acidic BVG rocks and is distinct from the other Lake District granites (O'Brien *et al.*, 1985). The Rb-Sr isochron age of 438 ± 6 Ma (Rundle, 1981) is Ordovician. The microgranite and its relationships with the Skiddaw Group and BVG are only exposed in the Bramcrag Quarry GCR site.

Lake District batholith

An elongate multicomponent batholith occurs at shallow depths beneath the central Lake District (Bott, 1974; Lee, 1986). This was probably emplaced as a set of stacked laccoliths (Evans *et al.*, 1993). The batholith is exposed in the west as the Eskdale and Ennerdale intrusions. Geological relationships (Branney and Soper, 1988) and their Caradoc age (452–450 Ma; U-Pb on zircon; Hughes *et al.*, 1996) suggest that these were subvolcanic, though they are geochemically distinct from the volcanic suites (O'Brien *et al.*, 1985).

The Ennerdale intrusion is well illustrated by the Bowness Knott GCR site, and lies to the west and NW of Wast Water (Figure 4.2). The intrusion is mostly in contact with the Skiddaw Group and BVG, but at the southern end of Wast Water it is possibly faulted against the Eskdale granite. It is a relatively thin tabular body, less than 2 km thick (Lee, 1989; Evans *et al.*, 1993). Granophyric-textured porphyritic granite is dominant, but dolerite, dioritic, and hybridized dioritic, granodioritic and melanocratic granitic rocks occur locally, adjacent to the margin of the intrusion.

The Eskdale intrusion comprises the Eskdale granite and the Eskdale granodiorite. The southern part of the granite is at the base, or within the lowest part, of the BVG, but northwards the contact rises to within a few hundred metres of the base of the Scafell Caldera succession. The granodiorite is a discordant intrusion that cuts through from the base of the BVG to the Duddon Basin succession. The Eskdale granite consists of medium-grained muscovite granite, aphyric and megacrystic microgranite, and coarse- to very coarse-grained granite.

Microgranite is most common in the northern part where the low-dipping contacts and inliers of hornfelsed volcanic rocks suggest that the roof zone of the intrusion is exposed. Xenoliths of country rock are extremely rare in the Eskdale granite and a thin zone of microgranite occurs at the margin. The main features of the intrusion are illustrated by the Beckfoot Quarry GCR site. Metasomatic recrystallization of the granite to quartz-white mica greisen occurs locally within all but the coarse facies of the Eskdale granite (Young *et al.*, 1988). Topaz is abundant in some greisens with accessory fluorite. A distinctive quartz-andalusite rock is associated with topaz greisen adjacent to the contact with the Skiddaw Group near Devoke Water (SD 1529 9733). The Eskdale granodiorite is typically medium grained, with hornblende and locally abundant biotite; it lacks muscovite. A marginal microgranodiorite is developed along the contact. Almandine garnet is locally present, particularly in rock exposed in the Waberthwaite Quarry GCR site.

Carrock Fell Complex

The multiple intrusions of the dyke-like Carrock Fell Complex were emplaced at the boundary between the Skiddaw Group and EVG in the north of the Lake District (Figure 4.4). It is the largest mafic intrusion in the Lake District; the characteristics of this layered intrusion are superbly illustrated in the Carrock Fell GCR site, but also feature in the Grainsgill GCR site. The layered cumulate gabbros of the Mosedale division are genetically related to the EVG (Hunter, 1980). Microgabbro, apatite-bearing ferrodioritic rocks and granophyric microgranite forming the Carrock division are related by fractional crystallization of a tholeiitic parent magma and were emplaced as a later dyke complex (Hunter, 1980). In the NW, later silicic bodies include the Harestones Rhyolite and lenticular micrographic microgranite intrusions emplaced along the Roughton Gill Fault. Radiometric dates of 468 ± 9 Ma (K-Ar, whole rock) and 435 ± 9 Ma (Rb-Sr, whole rock) for the Mosedale and Carrock divisions respectively probably indicate an Ordovician emplacement age (Rundle, 1979). The Silurian isochron for the Harestones Rhyolite (419 ± 4 Ma; Rb-Sr, whole rock) may be reset.

Haweswater basic intrusions

Gabbro, dolerite and dioritic rocks, cut by aplitic veins, and forming small outcrops totalling 2.6 km² are spread out over 19 km² on both sides of Haweswater (Figure 4.2; Haweswater GCR site). The intrusions were emplaced into the BVG. No radiometric date has been obtained, but cleavage in the rocks indicates an Early Palaeozoic emplacement age.

Late Caledonian intrusions

In the northern part of the Lake District the roof zone of the broadly cylindrical Skiddaw granite is exposed in the River Caldew, Grainsgill Beck and Sinen Gill (Lee, 1986). It is a coarse-grained biotite granite. At the northern end of the Grainsgill outcrop the granite passes into greisen, associated with mineralization that cuts both the granite and the adjacent Carrock Fell Complex. This significant feature is described in the Grainsgill GCR site report. The granite was emplaced into the Skiddaw Group and is surrounded by a classic, concentrically zoned aureole that grades outwards from cordierite-andalusite hornfels through cordierite-chiastolite and cordierite hornfels zones to spotted slates.

The sub-cylindrically shaped Shap granite cuts the BVG and adjacent Windermere Supergroup in the eastern Lake District (Figure 4.2). An extensive subcrop is present to the north of the outcrop (Lee, 1986). The pink and grey granite contains orthoclase megacrysts that are a distinctive and important petrogenetic feature (Shap Fell Crags GCR site). The intrusion is late Caledonian (397 ± 7 Ma; K-Ar; Rundle, 1992).

To the north of the Ennerdale intrusion an ENE-trending elongate zone of bleached and recrystallized Skiddaw Group rocks defines the Crummock Water aureole (Cooper *et al.*, 1988; Figures 4.2, 4.4). The metasomatic event has been dated at *c.* 400 Ma. The aureole is believed to be associated with a buried, highly evolved granite intruded along the northern margin of the Lake District batholith.

In the northern Pennines, the Lower Palaeozoic basement of the Alston Block is underpinned by the buried Weardale granite (Figure 4.1). The existence of this batholith was detected by geophysical surveys and confirmed by the Rookhope borehole (Dunham *et al.*, 1965; Bott, 1967). It is an aphyric two-mica granite, with pegmatitic and aplitic facies, and a sub-horizontal foliation. It is peraluminous and geochemically similar to the Skiddaw granite, a correlation that is supported by the Rb-Sr whole-rock isochron age of 410 ± 10 Ma (Holland and Lambert, 1970). The batholith is 60 × 25 km in extent, with cupolas such as the pink Dufton microgranite of the Cross Fell inlier (Hudson, 1937), rising from it. A further negative gravity anomaly over the Askrigg Block and the Raydale borehole confirmed the presence of the Wensleydale intrusion comprising pink, medium-grained granite (Figure 4.1; 400 ± 10 Ma; Rb-Sr, whole rock; Dunham and Wilson, 1985).

Minor intrusions

Suites of minor intrusions of diverse composition cut the Lower Palaeozoic rocks. Many of these are spatially and genetically linked with the major intrusions, but others illustrate a significantly greater range of magmatic compositions than is represented by the larger bodies. High-level intrusions associated with the Eycott and Borrowdale volcanic groups are intimately part of those groups. A brief description of the other suites is given below but no GCR sites specifically relate to the minor intrusions. Minor igneous intrusive bodies that crop out within GCR sites are described where appropriate.

Throughout the Skiddaw Group there are dykes, sheets and small plutons of porphyritic hornblende diorite, including augite spessartite, microdiorite, dolerite and olivine-augite hornblendite. These are calc-alkaline and are geochemically similar to the BVG; the K-Ar hornblende age of 458 ± 9 Ma supports the connection (Rundle, 1979). East of Cockermouth a suite of sills and stock-like intrusions of aphyric basalt, andesite and microgranodiorite is compositionally similar to the EVG and the Mosedale division of the Carrock Fell Complex. The Embleton Diorite from this suite has been dated at 444 ± 24 Ma by Rb-Sr (Rundle, 1979).

Aphyric basalt and dolerite dykes are abundant within the BVG around the Eskdale granite in Eskdale and Wasdale. The suite comprises high-Fe-Ti tholeiitic, and calc-alkaline, groups (Macdonald *et al.*, 1988). The latter may be associated with basalt lavas in the BVG, but the other is unique. No radiometric ages have been determined, but they are believed to span emplacement of the Eskdale granite.

Aphyric and sparsely microporphyritic rhyolite dykes are locally abundant within the BVG near the Eskdale and Ennerdale intrusions. The rocks are fine grained to cryptocrystalline and spherulitic. The dykes are genetically linked with the Ennerdale intrusion and the Rb-Sr isochron ages of 436–428 Ma are probably reset (Al Jawadi, 1987; Rundle, 1992).

Distinctive quartz-feldspar porphyry dykes occur sporadically throughout the Lake District. A geochemically variable suite of microdiorite–microgranite porphyry minor intrusions crop out in the Scafell area, in the Duddon valley and in the Windermere Supergroup. These may be linked with the Skiddaw–Shap intrusive episode as indicated by their geochemistry and by similar Rb-Sr isochron ages (Al Jawadi, 1987; Rundle, 1992).

Sparse, uncleaved, lamprophyre dykes cut all lithostratigraphical units within the Lake District and Cross Fell inliers. They are probably Early Devonian (Macdonald *et al.*, 1985). The Sale Fell minette (Eastwood *et al.*, 1968) is part of this suite.

EYCOTT HILL (NY 382 283–397 305)

D. Millward

Introduction

Located in the NE of the Lake District Lower Palaeozoic inlier, the Eycott Hill GCR site demonstrates a complete succession of lavas and interbedded volcaniclastic rocks of the Eycott Volcanic Group (EVG) (Figure 4.5) and may be regarded as the type section. The volcanic rocks are well exposed in typical trap topography of successive scarp and dip slopes. Ward (1876, 1877) first described the geology of Eycott Hill and included the sequence on a geological cross section. A detailed geological map and description of the succession is included in the Geological Survey memoir for the Cockermouth district (Eastwood *et al.*, 1968, pp. 70–72). The area is included in Geological Survey sheets 23 (1997) and 29 (1999).

For many years the volcanic rocks in the northern part of the Lake District were considered to be an outlier of, and were included within, the Borrowdale Volcanic Group (BVG). It was not until the geochemical work of Fitton (1971) that the northern volcanic rocks, including those of Eycott Hill, were shown to be dis-

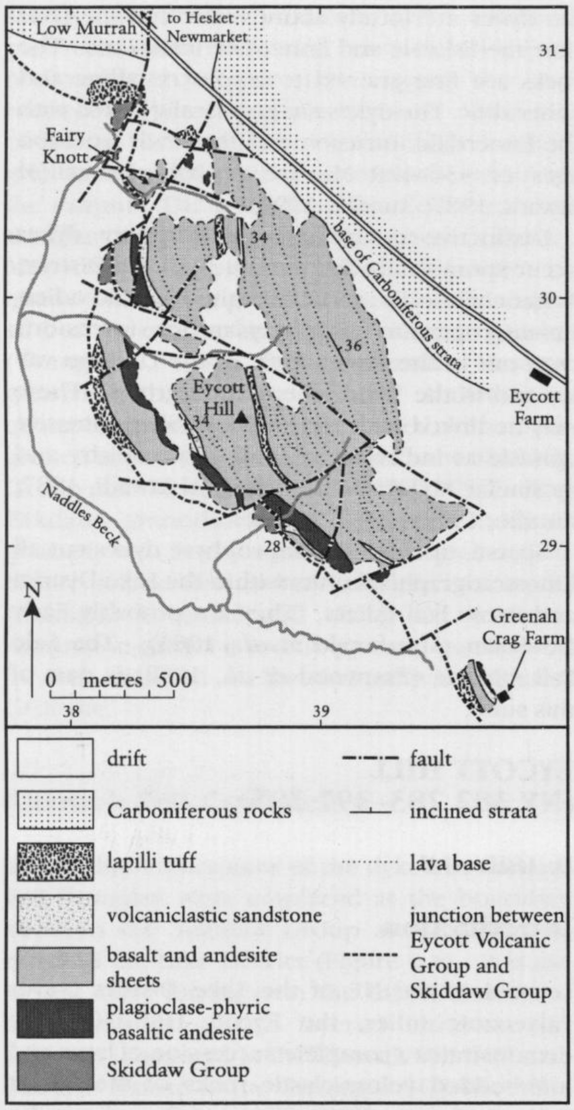


Figure 4.5 Exposure map of Eycott Hill (from Millward and Molyneux, 1992).

tinct from the larger outcrop in the central Lake District. A short while later the northern volcanic rocks were interpreted to be earliest Llanvirn in age and to overlie the Skiddaw Group conformably; they were then defined formally as the EVG (Downie and Soper, 1972). However, the age and basal relationship of the EVG have been challenged recently by Millward and Molyneux (1992) who mapped an unconformity at the base of the group and suggested that the Eycott and Borrowdale volcanic groups may have been contemporaneous. The site provides evidence crucial to the current understanding of the base of the EVG.

The site is also of historical interest because it is the type area for the distinctive orthopyroxene-plagioclase-megaphyric basaltic andesite, given the local name of 'Eycott-type' basaltic andesite by Eastwood *et al.* (1968) (Figure 4.6). Ward (1875, 1876, 1877) first described and illustrated these coarsely porphyritic rocks that contain feldspar crystals locally more than 2 cm long, and Teall (1888, pp. 225–228), in his classic work on the petrography of British rocks, described them in detail as 'labradorite-pyroxene-porphyrite'.

Description

The EVG in the GCR site is generally well exposed between Low Murrah and Greenah Crag Farm (Figure 4.5), consisting of an 800 m-thick succession of continental margin-type tholeiitic lavas and interbedded volcaniclastic rocks dipping eastwards at 30–40°. The volcanic rocks unconformably overlie Skiddaw Group mudstone of possible Cambrian age (Millward and Molyneux, 1992); the angular truncation of the uppermost lavas by the overlying basal beds of the Carboniferous cover rocks is well seen in the north of the GCR site (Figure 4.7).

More than 20 aphyric and highly porphyritic basaltic andesite and andesite lavas, varying from 20–90 m thick, constitute most of the sequence; several lava margins are present. Two 'Eycott-type' basaltic andesite lavas, each about 25 m thick, and one rhyolite crop out near the base of the sequence. Simple lavas dominate, having massive central zones, and becoming increasingly amygdaloidal towards the top and bottom; flow-banding and a fine-scale platy jointing parallel to the base are typically present in the lower part of the lavas. Rubbly flow-breccia indicates that most are aa-lavas. The lowest lava is heterogeneous with repeated alternations of massive and amygdaloidal, clinkery material suggesting that it is compound.

The lavas are typically porphyritic, containing up to 46% phenocrysts and glomerocrysts set in a fine- to very fine-grained groundmass of stumpy plagioclase laths, intergranular clinopyroxene, opaques and interstitial chlorite or dark-brown mesostasis, presumably after glass. A small number of lavas are aphyric or nearly so. Most of the phenocrysts are labradorite euhedra and scattered glomerocrysts; in the 'Eycott-type' basaltic andesite these may be up to 5 cm, but are mostly 1–1.5 cm. The plagioclase is fresh to turbid, typically with multiple and compound zoning. Small inclusions of chlorite or brown

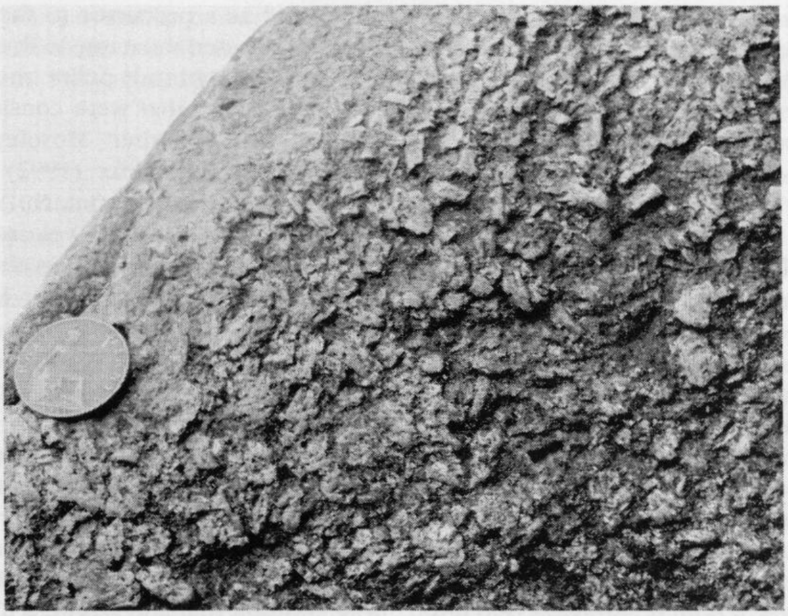


Figure 4.6 Pyroxene-plagioclase-megaphyric ('Eycott-type') basaltic andesite, Eycott Volcanic Group. The coin is 25 mm diameter. (Photo: BGS no. A6605.)

mesostasis are scattered throughout some crystals or in rings. Small 'rounded' anhedra of fresh clinopyroxene are present only in the lowest lavas on Eycott Hill. Chlorite pseudomorphs after orthopyroxene occur in basaltic andesite and andesite. Though Eastwood *et al.* (1968) reported pseudomorphs after olivine from elsewhere in the EVG, this mineral has not been found in rocks from Eycott Hill.

On the southern side of the inlier, less than 10 m of volcaniclastic rocks underlie the 'Eycott-type' basaltic andesite lavas, thickening to 90 m in the north. Thin interbeds, up to 5 m thick, are also present between andesites at higher lev-

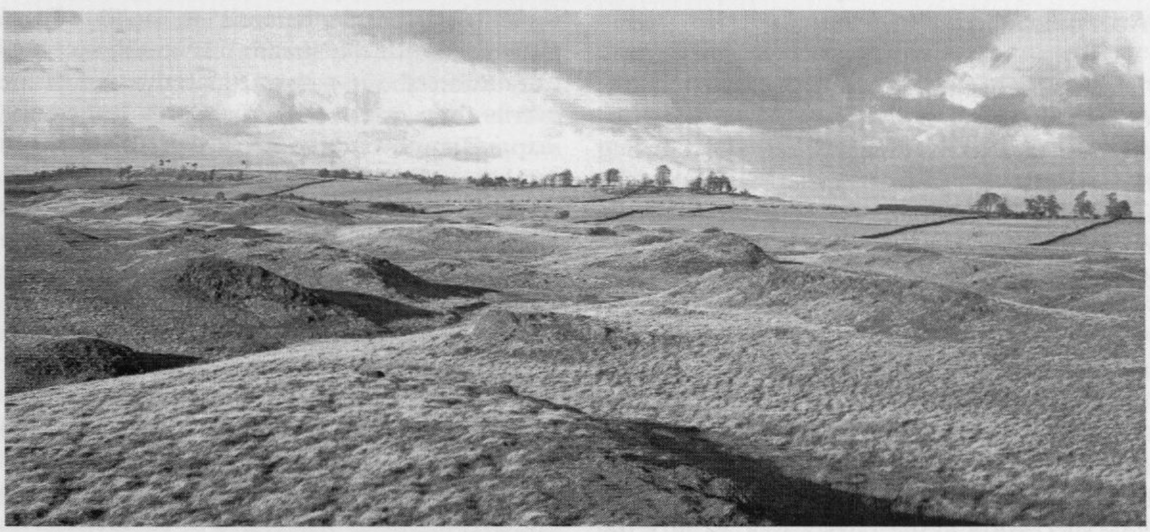


Figure 4.7 Eycott Hill: craggy scarp and dip-slope topography of the Eycott Volcanic Group in the foreground, contrasted with smooth, regular scarps in the overlying Carboniferous Limestone in the background. View looking NE. (Photo: BGS no. A6616.)

els in this sequence. These sedimentary rocks are generally parallel-bedded, fine- to coarse-grained volcaniclastic sandstone, though rock fragments in the soil on the west side of Eycott Hill (3829 3013) comprise graded, very coarse-grained sandstone and pebbly layers with mudstone clasts, presumably derived from the Skiddaw Group.

The basal unit of the succession west of Eycott Hill and at Greenah Crag Farm is a weakly bedded, poorly sorted lapilli-tuff comprising closely packed fragments of intensely amygdaloidal or wispy scoria along with angular to subrounded clasts of non-amygdaloidal, variously textured basalt, andesite and rhyolite; rare fragments of gabbro are present. These beds were probably deposited from mixed scoria-fall and hydroclastic eruptions. By contrast the basal, unbedded, massive, poorly sorted, matrix supported lapilli-tuff north of Fairy Knott is probably an ignimbrite.

A pinkish weathered welded dacitic lapilli-tuff, about 600 m in outcrop length and 20 m thick is present approximately 370 m above the base of the succession. This ignimbrite contains fiamme that are generally chloritized and contain coarse quartz-feldspar spherulitic devitrification. Crystal content comprises 16% plagioclase, 2.5% pseudomorphs after mafic minerals, and less than 1% granular opaque. Angular to subrounded, non-vesicular andesite clasts comprise the lithic component (4%).

Interpretation

The division of the middle Ordovician volcanic rocks in the Lake District Lower Palaeozoic inlier into separate lithostratigraphical units during the early 1970s marked a major change in the understanding of the history of the Lake District magmatic province, and arose from separate geochemical and biostratigraphical studies. Firstly, Fitton and Hughes (1970), and Fitton (1971) demonstrated clearly that the volcanic rocks of Binsey, the Caldbeck Fells and Eycott Hill show some tholeiitic characteristics compared with the calc-alkaline rocks of the central Lake District. Secondly, examination of microfloras from siltstone at the base of the volcanic succession in the Binsey area, west of the GCR site, led Downie and Soper (1972) to infer that the volcanic rocks are of earliest Llanvirn age. Thus, the northern volcanic rocks became known as the Eycott Volcanic Group, which was recognized as a precursor to the BVG. Wadge (1978) shortened the name to Eycott Group, but also included within it pelitic rocks in the eastern Lake District that were considered to be of similar age. Neither Moseley (1984) nor Millward and Molyneux (1992) followed this chronostratigraphical approach.

The relationship of the volcanic rocks to the underlying Skiddaw Group in the Lake District has been much in contention for many years (see Wadge, 1978, for summary). Eastwood *et al.* (1968) and Downie and Soper (1972) described passage beds comprising interbedded tuffaceous sedimentary rocks and andesite sheets at the junction in the west of the outcrop. However, Millward and Molyneux (1992, fig. 7) demonstrated a marked angular unconformity beneath these passage beds at the Chapel House Reservoir (2582 3551); biostratigraphical support showed that the Skiddaw Group beneath the mapped unconformity ranges in age from possible Late Cambrian to early Llanvirn. The andesite sheets in the passage beds were interpreted as sills and the sedimentary rocks designated as the Overwater Formation.

Ward (1876) showed a faulted contact on Eycott Hill and Eastwood *et al.* (1968) mapped a conformable base. A more complex basal relationship was discussed by Millward and Molyneux (1992). The characteristics of the lowest volcanic deposits vary along strike. North of Fairy Knott dark-grey, water-laid, laminated siltstone and silty claystone (Skiddaw Group) are overlain by a coarse, heterolithic, lapilli-tuff and tuff-breccia. In the stream just to the south of Fairy Knott about 4 m of tuffaceous sandstone overlie the Skiddaw Group and this bed can be mapped southwards to lie at least 120 m above the base of the volcanic sequence, with intervening pyroxene andesite and ash-fall lapilli-tuff. These lateral facies changes indicate emplacement of the volcanic rocks onto an existing topography.

The unconformable base and a succession predominantly of simple porphyritic lavas rather than volcaniclastic rocks demonstrate that the EVG has much in common with the Birker Fell Formation, the basal formation of the BVG. The sheeted andesite lava complex of the calc-alkaline BVG has been interpreted by Petterson *et al.* (1992) to have formed volcanoes with very shallow sides that constructed a plateau succession, probably within a graben-like structure. The geochemically distinct EVG may thus be interpreted as the product of similar constructions in a penecontemporaneous but separate volcanic field (Millward and Molyneux, 1992).

Conclusions

The Eycott Hill GCR site is significant as the type section for the Eycott Volcanic Group and for the well-known coarsely porphyritic 'Eycott-type' basaltic andesites. Crucial evidence for the onset of volcanism in the Lake District is present. More than 20 basaltic andesite and andesite aa-lavas, along with thin intercalations of pyroclastic and sedimentary rocks are well displayed by the crag and dip-slope topography. The volcanic rocks have some tholeiitic characteristics and were erupted onto an eroded landscape of Skiddaw Group rocks at the continental margin of Eastern Avalonia during the closure of the Iapetus Ocean. Despite geochemical differences with the Borrowdale Volcanic Group, the Eycott Volcanic Group exhibits a remarkably similar style of volcanism to the lower part of the former.

FALCON CRAG (NY 272 206–274 199)

B. Beddoe-Stephens

Introduction

Falcon Crag and Brown Knotts overlook the eastern shores of Derwent Water and provide a well-exposed, 650 m-thick succession of lavas and interbedded volcaniclastic rocks within the Birker Fell Formation, the basal part of the Borrowdale Volcanic Group (BVG). The volcanic succession dips gently to the east and forms a series of prominent terrace features, particularly on Brown Knotts, developed as trap topography (Figure 4.8). This GCR site is one of only three or four superb examples of this landform in the Lake District.

The GCR site (Figure 4.9) is an excellent and characteristic example of the largely subaerial, plateau-andesite field that is exposed extensively in the south-western, western and northern parts of the BVG outcrop and which developed as a precursor to large-scale ignimbrite volcanism and caldera collapse of the upper parts of the succession (Petterson *et al.*, 1992). Features that are typical of block- and aa-lavas are displayed by flows that are generally basaltic andesite to andesite in composition. In addition, the occurrence of some high-level, co-magmatic sills emplaced into wet volcaniclastic sediment are indicated by the presence of peperitic margins (Suthren, 1977; Branney and Suthren, 1988). The inter-relationships of primary and reworked pyroclastic rocks within the largely lava-dominated succession are also illustrated and of particular interest are volcaniclastic rocks formed by hydrovolcanic processes.

This area was first mapped and described by the Geological Survey (Ward, 1876). Remapping and re-interpretation of the rocks in terms of volcanic environments and sedimentary facies was undertaken by Suthren (1977). Extensive fieldwork in the area, and to the south by the Geological Survey (Petterson *et al.*, 1992) has shown that within the andesite-dominated lower part of the BVG the whole succession is considered best as one formation, with distinctive units defined as members.

Description

A generalized vertical section of the BVG rocks within the GCR site is shown in Figure 7.10. A major fault forms the eastern shore of Derwent Water and juxtaposes Skiddaw and Borrowdale Volcanic group rocks. However, the unconformity between the BVG and underlying Skiddaw Group is exposed nearby in Cat Gill, close to Kettlewell car park (268 194), and farther south near Troutdale Cottages (261 173). In the south of the GCR site, below Brown Knotts, the lowest unit in the succession is an aphyric andesite, very fine grained and typified by a conspicuous fluidal pilotaxitic texture in thin section. It commonly contains zones of internal brecciation, suggesting that it is probably a compound flow. In places it has a prominent laminar flow fabric. This andesite, up to 200 m thick, has been mapped extensively in Borrowdale and southwestwards to Dale Head. To the north, in the lower reaches of Cat Gill (270 210), a distinctive breccia appears to underlie the aphyric andesite and probably represents the basal bed of the BVG in this area. The breccia is reddish purple, massive and very poorly sorted with a polymict assemblage of typically highly angular volcanic clasts up to block size including pale-coloured, flow-laminated felsic rocks and darker andesitic scoria. Former pumiceous clasts and fragments are also present, as are rarer clasts of (Skiddaw Group) sedimentary lithologies.

Figure 4.8 Falcon Crag (left) and Brown Knotts showing the terraced, trap-like topography of lavas and interbedded volcaniclastic rocks. (Photo: B. Beddoe-Stephens.)

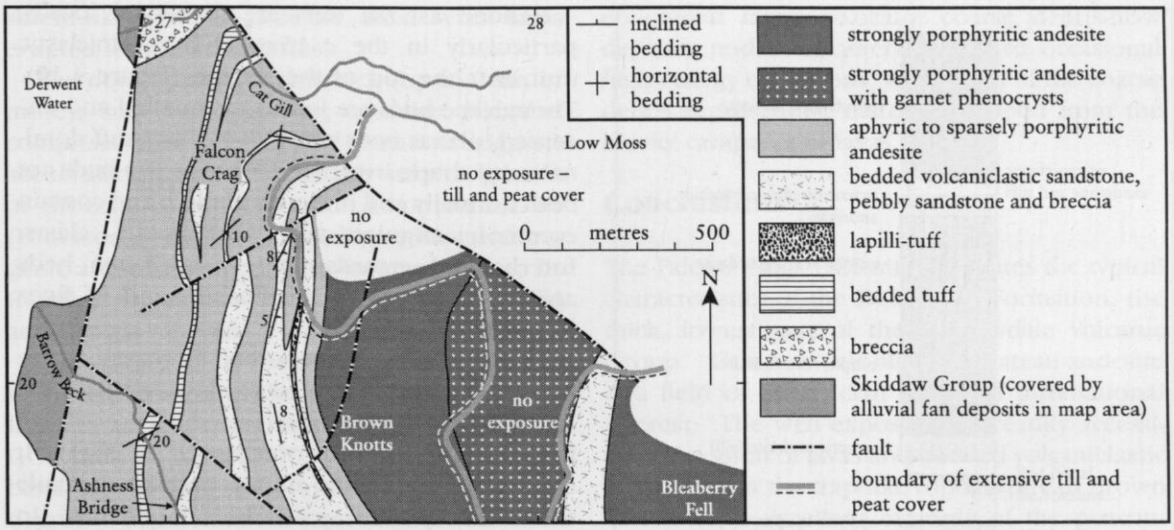


Figure 4.9 Map of the Falcon Crag GCR site.

The lower half of the succession (Figure 4.10) comprises generally sparsely porphyritic to aphyric fine-grained lavas with intercalated, bedded volcaniclastic units up to several tens of metres thick. The upper part is, by contrast, dominated by moderately to strongly porphyritic andesite. The lavas vary in thickness from 10–100 m (Figure 4.10), but in many cases have a low aspect ratio (thickness/extent ratio). This is particularly evident in the lower part of the section where a conspicuous trap-like topography forms the crags of Falcon Crag and Brown Knotts (Figure 4.8). Higher in the sequence the lavas are generally thicker and probably have higher aspect ratios.

The top, and locally the base, of the lavas are typically flow-brecciated, but the interiors are massive. Flow-breccias typically consist of angular to subangular, commonly amygdaloidal andesite blocks, and are clast supported. In the absence of volcaniclastic sandstone beds between lavas it is not always easy to establish whether a particular flow-breccia represents the top of one lava or the base of another, and in some cases a mixed breccia may form. The interstices of flow-breccias are commonly filled with finely laminated sediment washed in by percolating water. Autobreccia, in which solid blocks or crusts are re-incorporated into fluid lava, is present in the thick garnet-bearing andesite.

Within the central parts of some lavas, planar flow-laminae and jointing may be developed, usually parallel or sub-parallel to the base. In aphyric lavas at the base of the succession, flow-laminae or fine-scale banding form pervasively with superimposed platy jointing. A more discontinuous, irregular but sub-parallel flow-joint set is typically formed in the garnet-bearing andesite and the overlying andesite, which forms the summit of Bleaberry Fell.

The porphyritic andesites contain predominately plagioclase phenocrysts up to 2 or 3 mm with subordinate pyroxene (or pseudomorphs thereof). A thick lava that can be traced around the west and south sides of Bleaberry Fell, and forms the prominent knoll near the sheepfold (278 201), is distinctive for its conspicuous red garnet phenocrysts up to 5 mm across. In thin section these commonly have irregular, corroded margins. This same lava carries an accessory population of dark-coloured, irregular, rounded fine-grained diorite or dolerite xenoliths up to several centimetres across; on weathered surfaces these form recesses.

Though most of the andesites in the succession can be satisfactorily interpreted as lavas, there is evidence that some sheets were intrusive into volcaniclastic deposits. One thin, highly amygdaloidal and autobrecciated sheet terminates laterally in bedded sandstone indicating intrusion (2735 2015). Of more diagnostic value is the presence of peperitic upper margins, as described by Suthren (1977) and Branney and Suthren (1988), for the thin aphyric andesite on Brown Knotts (2744 2005).

Most of the volcaniclastic rocks are reworked,

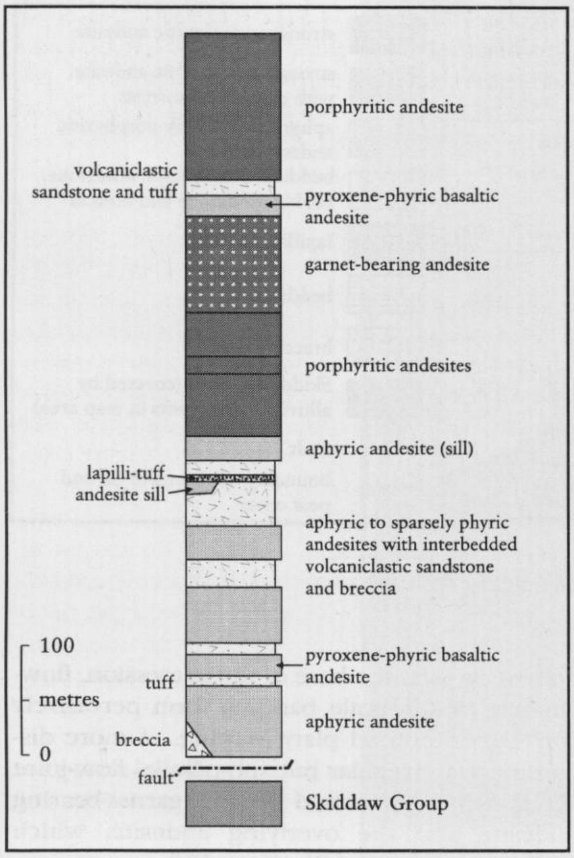


Figure 4.10 Generalized vertical section of Borrowdale Volcanic Group rocks between Brown Knotts and Bleaberry Fell; Falcon Crag GCR site.

comprising sandstone, pebbly sandstone and breccia. On the bench forming the top surface to the lower main face of Falcon Crag (271 205) are massive to weakly stratified pebbly sandstone and fine breccia with andesite clasts up to 20 cm suspended in a finer matrix. Clasts vary from subrounded to subangular. Structures typical of deposition by water are common, with abundant cross-bedding, sporadic ripple sets and rip-up clasts; erosional channels are common and are filled with coarser, gravelly lags. Silt- to sand-grade, planar bedded rocks also occur and these are affected by small-scale synsedimentary deformation locally. Examples of these features can be seen either side of the footpath from Ashness Bridge and traversing Brown Knotts (273 202). Boulder conglomerates, composed dominantly of andesitic lithologies, occur in lenticular masses or within eroded channels (e.g. at 2716 1993) and commonly contain lenses of bedded sandstone.

Bedded ash-fall tuffs are preserved locally, particularly in the *c.* 15 m-thick volcaniclastic unit near the top of the section (Figure 4.10). Though the beds are locally channelled and disrupted, planar beds of lapilli-tuff and tuff dominate and drape irregular surfaces. The beds are both normally and reversely graded, and contain common angular and scoriaceous clasts. Interbedded cross-laminated sandstone beds appear to represent the flushing out of fines from the ash deposits.

Lapilli-tuff occurs at several horizons in the succession. A massive to weakly stratified fine lapilli-tuff is well exposed at the base of the lower main face of Falcon Crag (2706 2043). It comprises abundant, highly angular juvenile clasts and sporadic paler lithic fragments. In thin section the clasts are predominantly devitrified glass; blocky to vesicular forms are present. An unbedded lapilli-tuff is exposed for a distance of about 1 km on Brown Knotts. It is about 10 m thick, occurs towards the top of the thickest volcaniclastic unit and locally overlies a thin sill (2737 2015). This lapilli-tuff is rather fissile because of a prominent low-angle foliation produced by the alignment of abundant, dark fiamme-like fragments. It also contains common angular, andesitic to felsitic lithic lapilli in a fine-grained matrix, which includes siltstone fragments.

Interpretation

The GCR site illustrates most of the features that are critical to the recent interpretation by Petterson *et al.* (1992) of the Birker Fell Formation, the lowest unit of the BVG. The conspicuous trap-like topography of dominantly andesite lava interbedded with volcaniclastic rocks is well illustrated in the crags of Falcon Crag and Brown Knotts. In his analysis of the volcanic environment in which this succession was deposited, Suthren (1977) noted the lack of evidence for any significant topographic relief, such as might be expected on a steep-sided stratocone. The lavas form tabular sheets broadly concordant with the intercalated, laterally persistent, bedded volcaniclastic rocks that must have been deposited sub-horizontally. Thus, lava extrusion occurred over a subdued, flat-lying landscape. Using evidence from the western part of the BVG, Petterson *et al.* (1992) concluded that extensive areas of the Birker Fell Formation aggraded as a subaerial, flat-lying or shield-like plateau-andesite field with lavas erupted from many centres.

The development of the thick (up to 2 km or more), subaerial, flat-lying andesite pile that comprises the Birker Fell Formation suggests accumulation within an actively subsiding basin or rift zone developed within a continental arc (Petterson *et al.*, 1992). Analogies in active orogenic arcs of this type of environment are to be found in Japan, New Zealand, the western USA and Central America.

The volcaniclastic rocks are also important in the interpretation of the volcanism and several features are illustrated in the succession of the GCR site. Suthren (1977) interpreted the local basal breccia as a mass flow deposit. The high degree of fragmentation, form and vesicularity of the juvenile fragments and presence of substrate material suggest an explosive hydromagmatic origin, though subsequent reworking of such a deposit to form debris flows is likely and cannot be excluded. A further example of rocks probably formed by hydroclastic processes is the massive to weakly stratified fine-grained lapilli-tuff, containing predominantly devitrified glass, that is well exposed at the base of the lower main face of Falcon Crag (2706 2043).

The distinctive, unbedded lapilli-tuff on Brown Knotts illustrates the problems inherent in the interpretation of ancient pyroclastic rocks. Suthren (1977) interpreted the lapilli-tuff as a welded ignimbrite, because of the eutaxitic-like fabric. Many of its characteristics are consistent with its origin as a lithic-rich ignimbrite. However, the fabric may not have been the result of welding. Alteration of pumice to clay minerals may occur rapidly after deposition, causing loss of strength within the clast (Branney and Sparks, 1990). Collapse of the vitroclasts may then occur through subsequent loading and resulting in a fabric that resembles the effects of welding. Alternatively, this rock may have had a phreatomagmatic origin.

In common with much of the BVG, there is no evidence (faunal or lithological) that volcanism was submarine (Branney, 1988a). However, the presence of hydroclastic tuffs towards the base of the sequence in this GCR site possibly indicates that periodically subaqueous conditions were present. Other volcaniclastic beds record the extensive reworking by runoff (transient fluvial systems or sheetwash) of ash-fall deposits and re-deposition as planar- and cross-bedded sandstone, or turbidite-like mass flows into ephemeral lakes. Locally, coarse debris-flow deposits and conglomerates record occasional high-energy conditions, with much of the coarse debris representing material stripped from the blocky carapaces of lavas.

Conclusions

The Falcon Crags GCR site illustrates the typical characteristics of the Birker Fell Formation, the thick, lowest part of the Borrowdale Volcanic Group. This rare calc-alkaline plateau-andesite lava field of Ordovician age is of international interest. The well exposed and readily accessible succession of lavas and bedded volcaniclastic rocks seen in the trap-like topography of Brown Knotts is an excellent example of the plateau-andesite lava field that dominated the early stage of volcanism. However, the dominantly reworked material in the volcaniclastic rocks was probably derived from the reworking of unconsolidated pyroclastic deposits, and illustrates the low-preservation potential of the latter within the geological record; pyroclastic and hydroclastic eruptions were far more common during the volcanic episode represented by the Birker Fell Formation than is recorded specifically in the succession.

RAY CRAG AND CRINKLE CRAGS (NY 241 038–NY 265 055)

M. J. Branney

Introduction

West of Great Langdale, the Ray Crag and Crinkle Crags GCR site provides exceptional exposures of the Borrowdale Volcanic Group (BVG) succession within the Scafell Caldera (Figures 4.11, 4.12). The volcanic rocks record the eruptive history of a caldera-collapse cycle that fluctuated from magmatic to phreatomagmatic as vent regions were periodically flooded during the subsidence (Branney and Kokelaar, 1994a). The phreatomagmatic eruptions were large in scale; one of the ash-fall layers records the largest magnitude phreatoplinian eruption yet documented (Branney, 1991), and evidence for its origin by subaerial fallout and for its subsequent seismically induced deformation when the caldera subsided is superbly exposed. The exhumed internal structure of the Scafell Caldera shows how it fractured into many fragments as it collapsed;

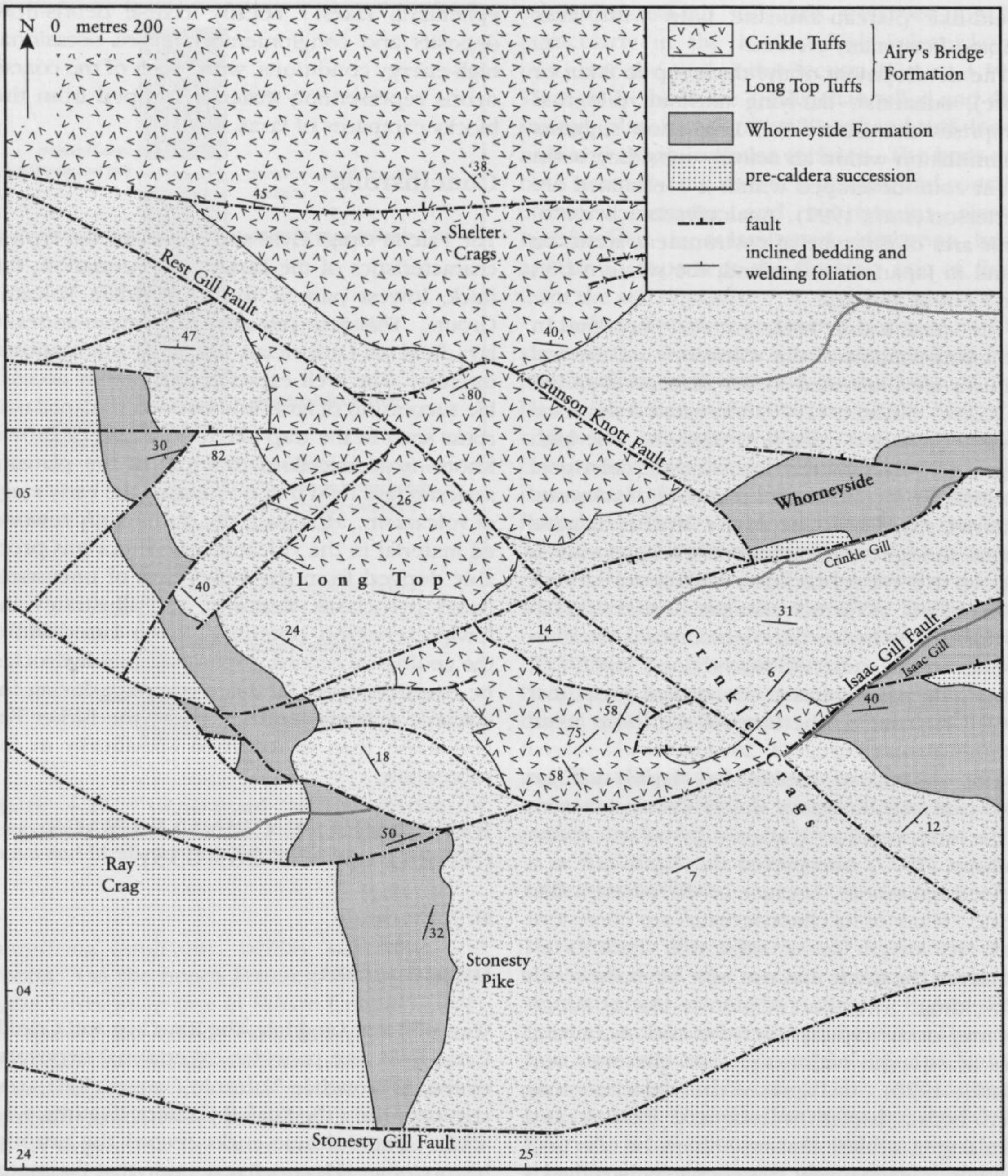


Figure 4.11 Simplified map of the Ray Crag and Crinkle Crags GCR site (mapping by M. J. Branney, 1988b).

this has become known as 'piecemeal' caldera collapse. Criteria to distinguish volcanotectonic faults and to determine movement histories are exhibited in cross section on Crinkle Crags. Many of the faults show complex movement histories, and the fault scarps they produced shed rock avalanches into the subsiding caldera. Tuff-filled fissures and a graben at Crinkle Crags record localized extension caused by downsagging of the caldera floor during subsidence (Branney, 1995).

The geology of Crinkle Crags was described by Green (1913), Hartley (1932), and Oliver (1961), but it was not until the late 1980s that the 15 km-diameter Scafell Caldera was recognized (Branney and Soper, 1988; Branney, 1988b; Davis, 1989). The GCR site is of international importance because it provides unique information about the architecture of large hydrovolcanic calderas, and shows how their eruptions and collapse geometries evolve during subsidence. Type localities of many of the formations and members that comprise the caldera-fill succession are within the site. Fuller descriptions of the many geological features exhibited are given in Branney (1988b, 1990a, 1991, 1995), Davis (1989), Branney *et al.* (1992) and Branney and Kokelaar (1994b, 1994c); geological maps of the Scafell Caldera are published by the British Geological Survey as 1 : 50 000 sheets 29 (1999) and 38 (1996), and in Branney and Kokelaar (1994a).

Description

The oldest rocks within the GCR site are lavas that pre-date the onset of the major explosive volcanism associated with the Scafell Caldera (Branney, 1988b, 1990a). On Ray Crag (243 042), west of Crinkle Crags, thin subaerial, amygdaloidal pahoehoe, aa, and blocky basaltic-andesite lavas are displayed, probably to the best advantage of any locality in Britain (Figure 4.11). The lavas are interstratified with thin beds of basic tuff and volcaniclastic sedimentary rock. These belong to the Lingcove Formation of Branney and Soper (1988) and Branney and Kokelaar (1994a) and Ray Crags is the type locality for the formation. Petterson *et al.* (1992) and Millward *et al.* (in press) included these rocks as part of the Throstle Garth Member of the Birker Fell Formation.

Spectacular, continuous exposures around the southern part of Crinkle Crags are the type area of the Whorneyside Formation, the product of the first major explosive phase of the Scafell Caldera; the type area is named after Whorneyside Force (2615 0535) (Branney, 1991). The formation is composed of an andesitic ignimbrite that passes up into an approximately 30 m-thick, thinly bedded andesitic ash-fall tuff with small accretionary lapilli and ash pellets. Ash-shower fallout onto a land surface is indicated by the size grading and stratification, by fallout layers that drape small steep-sided erosional rills cut by ephemeral streams, and by an absence of subaqueous facies (Branney, 1991). Impact structures occur at the base of some larger fallout lithic clasts (2488 0406), the maximum size of which increases systematically northwards, indicating a vent position to the north (see the Sour Milk Gill GCR site report for comparative description of subaqueous facies of the Whorneyside Formation). However, the average grain size remains constant and fine grained with distance from the source. This is a typical feature of phreatoplinian ashes. The tuff is extensively and spectacularly deformed, with multiple soft-state thrusts in some places (e.g. at Stonesty Pike, 2488 0402) and extensional faults elsewhere. These probably record surficial gravity sliding and lateral spreading during caldera collapse. A superbly displayed angular unconformity north of Stonesty Pike (at 2487 0420) shows white silicic tuff of the Airy's Bridge Formation draping the irregular top of the deformed andesitic tuff.

An andesite sheet south of Rest Gill (at 242 054) may record a late phase of the Whorneyside eruption. It is instructive because at outcrop, it closely resembles an autobrecciated, flow-banded block-lava buried by the overlying Airy's Bridge Formation tuffs, but mapping shows that it is a sill intruded into the phreatomagmatic tuff. In contrast to other high-level sills like the one described in the Pets Quarry GCR site report, this sill does not show textural features that are diagnostic of an intrusive origin, such as spalled hydroclasts and local steam-vesiculation of the host deposit; it would probably be taken to be a lava but for its locally discordant contacts.

The overlying Airy's Bridge Formation, the type area of which is on Crinkle Crags, is divided into two. The lower part, the Long Top Tuffs, is superbly exposed on Long Top (246 047), and comprises approximately 120 m of welded silicic ignimbrites interstratified with thin units of non-welded phreatomagmatic tuff (Figure 4.12). The silicic ignimbrites vary from bedded to massive and most are intensely welded. The lowest phreatomagmatic tuff layer is the Stonesty Tuff, a bedded, white, flinty, formerly vitric, tuff with abundant accretionary lapilli (type locality: Stonesty Pike, 2488 0403; Figure 4.11). Its thickness variation suggests that the source vent lay to the south. The next two phreatomagmatic beds, the Cam Spout Tuff (2445 0474) and the Hanging Stone Tuff (2841 0442), are both extensive, cream-coloured accretionary lapilli-bearing, cross-bedded pyroclastic surge and ash-fall layers, that record phreatomagmatic eruptions from vents to the north of Crinkle Crags.

The upper part of the Airy's Bridge Formation, the Crinkle Tuffs, comprises silicic ignimbrites that are more intensely welded than

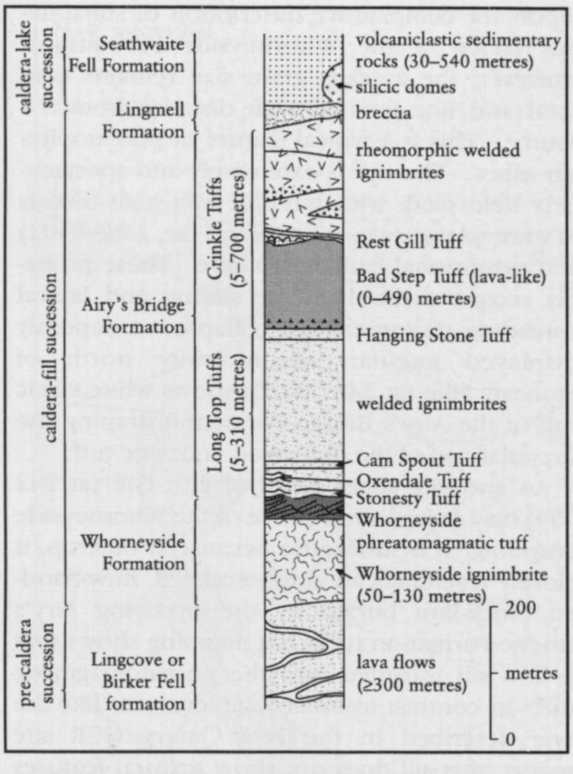


Figure 4.12 Generalized lithostratigraphy of the Scafell Caldera succession (after Branney and Kokelaar, 1994a).

the underlying Long Top Tuffs, and contain superb rheomorphic folds and lineations. The lowest of these ignimbrites is the garnetiferous Bad Step Tuff (type area: Bad Step, 2487 0481, near the summit of Crinkle Crags). This unit is of particular interest because it shows extreme welding. It is flow-banded, flow-folded, autobrecciated and lava-like, and is indistinguishable from a rhyolite block lava, except near its base where, instead of having a widespread basal autobreccia that is typical of block-lavas, it is commonly unbrecciated and has well-preserved pyroclastic textures. Around Bad Step, and on the eastern slopes of Shelter Crags (2530 0553), the basal part of the Bad Step Tuff is a poorly stratified pyroclastic breccia with a welded tuff matrix. The fiamme-bearing eutaxitic matrix has siliceous nodules and grades upward into lava-like rock with siliceous nodules, indicating that the entire unit was deposited by a single hot pyroclastic flow (Branney *et al.*, 1992). The breccia is a rare UK example of a co-ignimbrite lag breccia (Walker, 1985), commonly used to indicate proximity to ignimbrite source vents.

The Bad Step Tuff is separated from overlying rheomorphic ignimbrites of the Crinkle Tuffs by the Rest Gill Tuff, a distinctive, laminated, turquoise fine to coarse tuff, less than 2 m thick, and thought to be the product of an extremely wet phreatomagmatic eruption. It is named after Rest Gill (2446 0558) where it is well displayed, showing evidence of contemporaneous local reworking by surface water. The overlying thick, massive, garnetiferous welded ignimbrites have eutaxitic and parataxitic welding fabrics,

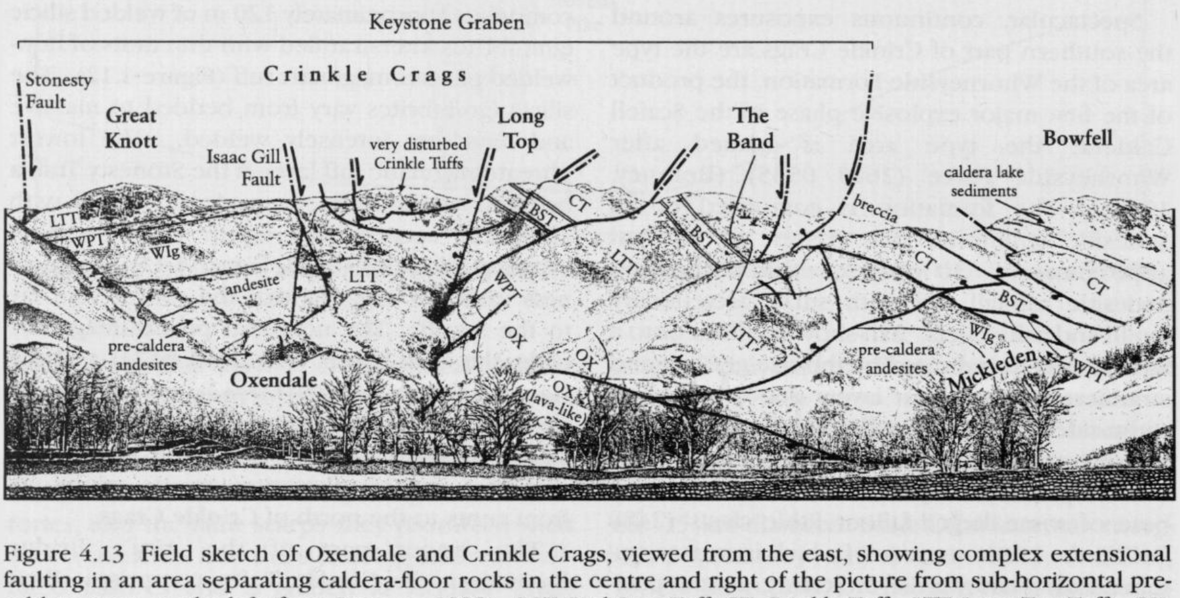


Figure 4.13 Field sketch of Oxendale and Crinkle Crags, viewed from the east, showing complex extensional faulting in an area separating caldera-floor rocks in the centre and right of the picture from sub-horizontal pre-caldera strata on the left (from Branney, 1995). BST, Bad Step Tuff; CT, Crinkle Tuffs; LTT, Long Top Tuffs; OX, Oxendale Tuff; WIg, Whorneyside ignimbrite; WPT, Whorneyside phreatomagmatic tuff.

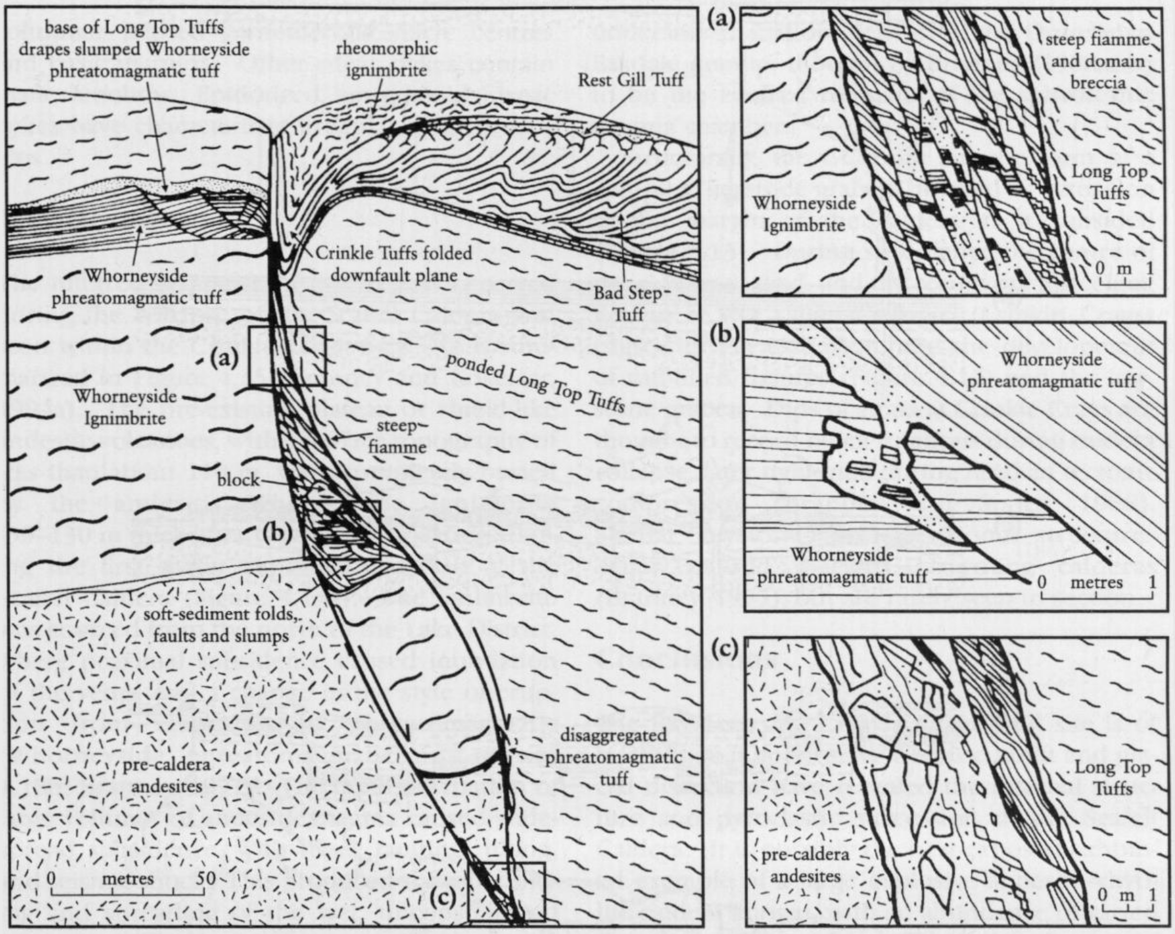


Figure 4.14 Field sketches of a volcanotectonic fault at Isaac Gill, viewed facing SW. Inset (a) gives details of disrupted bedded tuff of the Whorneyside Formation within the fault zone. Inset (b) shows homogenized tuff along one of the many slide surfaces in the bedded tuff with footwall pull-apart structures and locally derived intraclasts. Slumped bedded tuff dips steeply towards the downthrow side of the main fault. Inset (c) shows mixing of blocks of ignimbrite and homogenized tuff (from Branney and Kokelaar, 1994a).

the latter with a rheomorphic lineation; locally in high-strain zones the fabric is flow-banded. The ignimbrites contain numerous lenses of mesobreccia, formed from rock avalanches produced by unstable, growing caldera-fault scarps. Some mesobreccia has a welded tuff matrix (e.g. at 2487 0559) and fiamme have been deformed plastically around rigid blocks during compaction while the deposit was still hot.

The internal structure of the Scafell Caldera is well displayed on Crinkle Crags. Many closely spaced volcanotectonic faults are exposed in plan and in section (Figures 4.11, 4.13). For example, the Isaac Gill Fault (Figure 4.14) is a superb example of a caldera-floor fault that moved prior to the lithification of wet phreatomagmatic tuff, and before some of the ignimbrites cooled down and became brittle (Branney, 1988b). On the east side of Crinkle Crags, the Whorneyside phreatomagmatic tuff has slumped down the fault plane resulting in steeply inclined bedding, intense soft-state disruption, disaggregation, and local incorporation of angular blocks of Whorneyside ignimbrite. Welded silicic ignimbrites show evidence of hot ductile shear and folding adjacent to the volcanotectonic faults (Figure 4.14). The thickness of successive pyroclastic units changes abruptly across the faults, which allows the complex movement history of individual faults to be constrained (Branney and Kokelaar, 1994a).

Acid and basic dykes cut the succession at Crinkle Crags, for example on Stonesty Pike (2491 0385), Great Cove (2515 0470) and Rest Gill (2448 0520). They include porphyritic rhyolite and altered basalt; composite dykes have

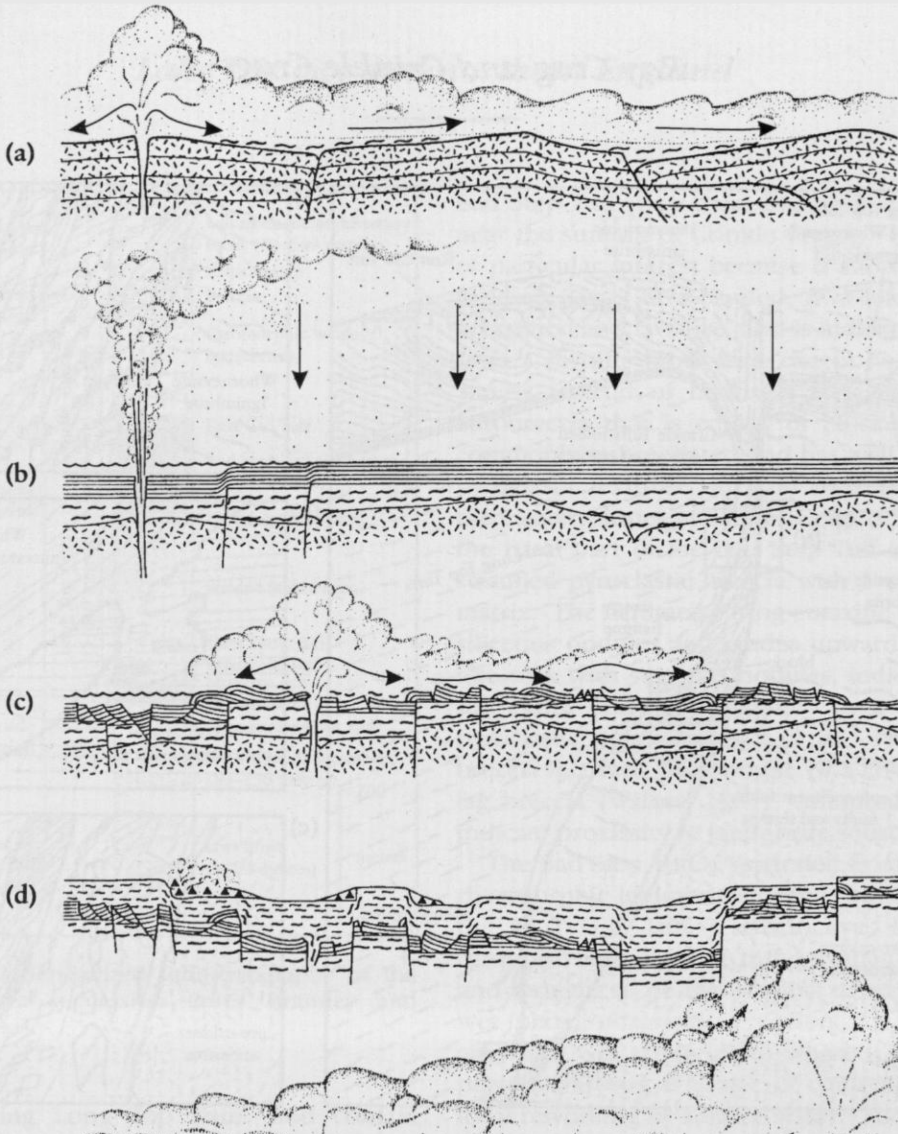


Figure 4.15 Schematic summary of the evolution of the Scafell Caldera by piecemeal collapse. The cartoons are simplified and not to scale. (a) Emplacement of the Whorneyside ignimbrite across low-profile andesite volcanoes. (b) Proximal subsidence facilitates aqueous inundation of the vent, changing the eruption style to phreatoplinian (see the Sour Milk Gill GCR site report). (c) Onset of widespread piecemeal subsidence, deformation of Whorneyside phreatomagmatic tuff deposits and burial under hot silicic ignimbrites of the Long Top Tuffs erupted from new vents. (d) Continued subsidence with ductile deformation of hot ignimbrites and collapse of growing fault scarps. (e) Final stages of the paroxysmal eruption of the Crinkle Tuffs. (f) Caldera lake formation with deposition of subaqueous volcaniclastic sediments, along with post-collapse silicic dome emplacement (see the Rosthwaite Fell GCR site report) (from Branney and Kokelaar, 1994a).

columnar jointed garnetiferous silicic centres and basic margins. Other silicic dykes contain mafic xenoliths. Epidotized, amygdaloidal basic dykes have characteristic irregular, chilled margins.

Interpretation

The inferred sequence of events that occurred during the collapse of the Scafell Caldera and seen within the Crinkle Crags GCR site is summarized in Figure 4.15 (Branney and Kokelaar, 1994a). The pre-existing plateau or shield-like andesite volcanoes, with a surface topography of less than about 110 m, were completely buried by the andesitic Whorneyside ignimbrite (50–130 m thick after welding compaction) during the first major explosive eruption of the Scafell Caldera (Figure 4.15a). The ignimbrite was sourced from the north of the Lake District, where proximal subsidence caused inundation of the vents, and a change in the style of eruption from magmatic to phreatomagmatic (Whorneyside phreatomagmatic tuff; Figure 4.15b; Branney, 1991). The rapid evacuation of large volumes of andesitic magma caused widespread subsidence, with block faulting, tilting, and seismic shock. This produced soft-state sliding and spreading of the wet, unconsolidated fallout tuff (Figure 4.15c). It also caused a change in vent position and the onset of silicic explosive ignimbrite eruptions, that rapidly buried and preserved the slumped Whorneyside phreatomagmatic tuff (Figure 4.15c). There followed a fluctuation between explosive magmatic eruptions producing hot ignimbrite and violent phreatomagmatic eruptions (Long Top Tuffs). Piecemeal caldera subsidence continued, and the hot ignimbrites deformed in a ductile manner at the numerous active volcanotectonic faults (Figure 4.15d). The fault scarps collapsed locally, generating hot rock avalanches. During the climax of the eruption, thick high-grade rheomorphic ignimbrites were emplaced and localized subsidence accelerated (Figure 4.15e). Finally, the caldera became flooded, forming a large caldera lake (Figure 4.15f). The subaqueous sedimentary rocks and tuffs that buried the caldera-fill ignimbrites, and the post-collapse silicic domes are considered in the Langdale Pikes and Rosthwaite Fell GCR site reports. The succession was subsequently intruded by dykes and pervasively altered hydrothermally, a typical feature of modern caldera fills. The area is underlain at shallow depths by the Ordovician Eskdale granite, thought by Branney (1988a, b) to be the evolved remnant of the subvolcanic magma chamber.

Structurally, the GCR site has the form of a complex 'keystone graben', formed by extension at the margin of the caldera as it subsided (Figure 4.13). During subsidence the centre of the caldera sagged, and the resultant monoclinal flexing at the caldera margin (Crinkle Crags) caused brittle extension, and the development of tuff-filled fissures (Figure 4.14) and the keystone graben. Dips of strata at Crinkle Crags are thought to record block rotations during caldera collapse, later tightened during Acadian tectonic compression (Branney and Soper, 1988). Similar keystone-type extensional structures occur around margins of young calderas (Branney, 1995), but are rarely seen in section.

Conclusions

The Ray Crag and Crinkle Crags GCR site is of international importance because uplift and glacial dissection have revealed the internal structure and pyroclastic succession of the Scafell Caldera. It is possibly the best-exposed exhumed example of a large explosive andesite–rhyolite caldera known, with an abundance of varied deposits produced by the explosive disintegration of magma by water. Most modern calderas of this type are inaccessible because they are flooded or buried by their erupted products. Therefore, an understanding of the Scafell Caldera provides important insights into the evolution and possible internal structure of modern, hazardous, flooded caldera volcanoes, like Taal (Philippines), Santorini (Greece), Kikae (Japan) and Rabaul (Indonesia).

Crinkle Crags exhibits a 'piecemeal' caldera structure resulting from the differential foundering of adjacent caldera-floor fault blocks. Such complexity was not widely envisaged for calderas prior to the 1980s. Several continuously exposed faults can be traced down through the caldera stratigraphy into the caldera floor. These faults grew in a complex way during the eruption, and they display features that readily distinguish them from other types of faults. The stratified caldera-fill succession allows reconstruction of how a caldera subsides progressively with time, and how the corresponding eruptive activity varies. Most caldera fills studied previously are non-stratified, preventing detailed reconstruction of caldera evolution during collapse.

Crinkle Crags is the type locality of the Whorneyside Formation, which records the largest-magnitude explosive eruption yet documented that was produced by large volumes of water coming into contact with magma. The GCR site is also the type area for the Airy's Bridge Formation, which includes some of the best examples in Britain of cross-bedded pyroclastic surge deposits, garnet-bearing welded ignimbrites, avalanche deposits, and lag breccia associated with ignimbrite. The very densely welded ignimbrites, including one that is so intensely welded that it resembles a flow-banded, flow-folded lava, are unusual among calc-alkaline ignimbrites. Finally, on Ray Crag are excellent examples of pahoehoe, aa and blocky basic lavas that were erupted prior to the major explosive phase of the Scafell Caldera.

SOUR MILK GILL (NY 235 122)

M. J. Branney

Introduction

The Sour Milk Gill GCR site contains a superb record of volcanic and sedimentary processes that occurred during a major explosive eruption in a volcanic lake that was proximal to the vent (Figure 4.16). The rocks were produced by the first major explosive eruption associated with the Scafell Caldera (Figure 4.12; Branney and Kokelaar, 1994a). They belong to the Whorneyside Formation, which comprises an ignimbrite overlain by a bedded phreatomagmatic tuff (Figure 4.12). Substantially more than 100 km^3 of magma were erupted, burying the western Lake District beneath more than 30 m of fallout ash (Branney, 1991). This ash-fall layer is believed to record the largest magnitude phreatoplinian eruption yet documented (Branney, 1991). Facies associations, and the size of impacted lithic clasts in the tuff indicate that the volcanic vent lay just to the NW of Sour Milk Gill, where subsidence had created a large volcanic lake, possibly connected to the sea. Though the recent interpretation of the bedded tuff succession in the Whorneyside Formation is the main reason for the selection of this GCR site, the overlying Airy's Bridge Formation also contains important features that are additional to those seen in the Ray Crag and Crinkle Crags and Rosthwaite Fell GCR sites.

Oliver (1961) did not distinguish the succession at Sour Milk Gill from the dominantly

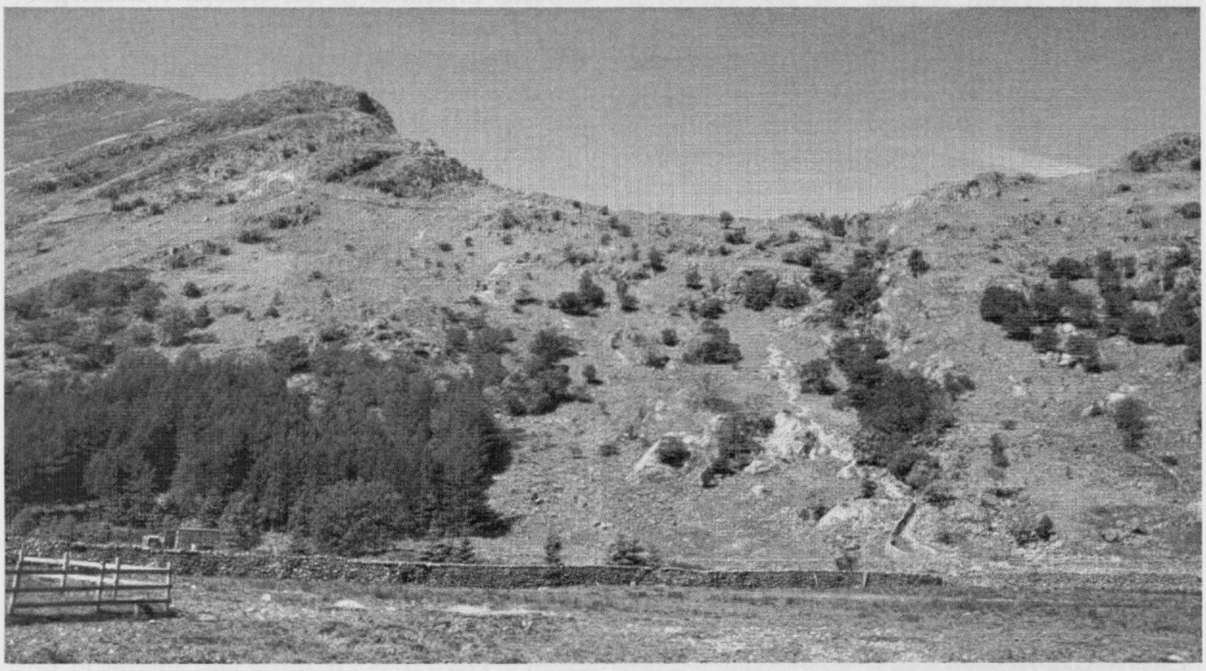


Figure 4.16 Sour Mill Gill from Seathwaite Farm, Borrowdale. Southward-dipping proximal lacustrine Whorneyside phreatomagmatic tuff (centre of the picture), intruded by andesite sills (right) is overlain by silicic ignimbrites of the Airy's Bridge Formation (left). (Photo: M. J. Branney.)

andesitic lower part of the Borrowdale Volcanic Group (BVG). The rocks at Sour Milk Gill were described in detail first by Suthren (1977) and Suthren and Furnes (1980), who recognized the lacustrine character. Branney (1988b, 1991) presented evidence that these rocks are the proximal facies of the Whorneyside phreatoplinian eruption. Davis (1989) interpreted the overlying Airy's Bridge Formation and a further account of the area is by Suthren and Davis (1990). The following details are derived mainly from the most comprehensive account by Kokelaar and Branney (1999). Arthropod tracks have been recorded from a loose block of bedded volcaniclastic rocks from this site (Johnson *et al.*, 1994).

Description

Strata at Sour Milk Gill dip 50° S, towards the centre of the Scafell Caldera. On the north side of Sour Milk Gill a stack of andesite sills, more than 300 m thick, dips beneath the 160 m-thick stratified upper part of the Whorneyside Formation (Figures 4.12, 4.17). The sills were intruded into wet ash and sediment during, and shortly after, the Whorneyside eruption, and their upper contacts locally show discordant, invasive, apophyses of peperite (see the Pets Quarry GCR site report for discussion of peperite). The Whorneyside ignimbrite crops out farther NE, where it underlies the sills.

To the SE of Sour Milk Gill, for example around Seathwaite Farm, the Whorneyside phreatomagmatic tuff is subaerial. Its pyroclastic origin is indicated by abundant accretionary lapilli, ballistic lithic blocks with impact structures, and draping of topography. The parallel thin stratification records unsteady ash-shower fallout from a vast umbrella cloud (Branney, 1991). Rainfall during the eruption produced surface water that eroded minor rills into the subaerial ash. The 'V'-shaped fluvial rills draped by succeeding fallout ash layers (2422 1222) are probably the best examples seen in Britain.

At Sour Milk Gill the ash fell into shallow, standing water. Volcaniclastic lithofacies have been divided into six categories (Kokelaar and Branney, 1999), listed here in decreasing order of abundance:

1. Parallel-stratified very fine to very coarse tuff, interpreted as lithified fallout ash, exhibits rare impact structures, and can be subdivided into water-settled and subaerial varieties, based on the lamination and grading patterns, and on occurrences of loading structures and polygonal desiccation cracks.
2. Massive to laminated, fine-grained to pebbly sandstone, in places with matrix-supported intraclasts and/or dewatering structures, is thought to have been deposited by shallow-water turbidity currents.
3. Cross-laminated, scoured and rippled siltstone and sandstone, is interpreted to represent wave and current reworking of fallout ash in shallow water.
4. Lenticular beds, up to 4 m thick, of very poor-

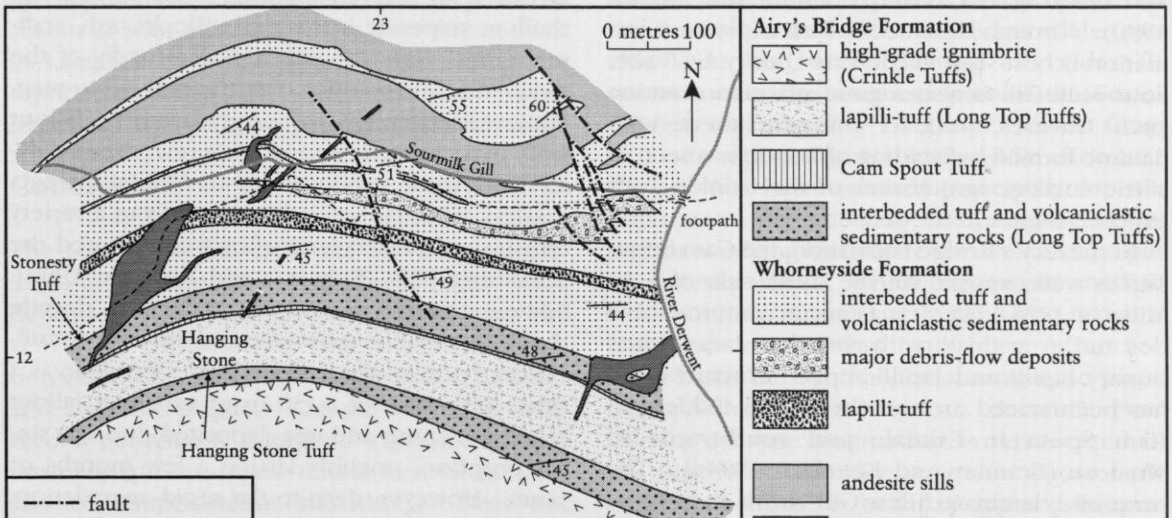


Figure 4.17 Simplified map of Sour Milk Gill (after Kokelaar, in Kokelaar and Branney, 1999).

ly sorted, block-rich sandstone and breccia are interpreted as debris-flow deposits. Most blocks are of andesite and are probably derived from proximal ballistic fallout and/or high-level intrusions that emerged onto the lake floor. One bed contains numerous blocks of subaerial tuff containing accretionary lapilli, and must have been derived from the lake shore.
5. Rare cross-stratified, medium- to very coarse-grained sandstone and gravel conglomerate is thought to have been deposited from dilute stream-flow currents that caused migration of sediment sheets and dunes.
6. Poorly sorted, parallel-stratified medium- to very coarse-grained sandstone and gravel conglomerate, with some low-angle truncations, is interpreted to represent deposition from laminar hyperconcentrated currents. A unit of massive, andesitic lapilli-tuff, 11 m thick, is considered to be a non-welded ignimbrite, and is overlain by a probable co-ignimbrite fallout tuff with accretionary lapilli.

The succession passes up into the Long Top Tuffs, which here comprise interbedded and mixed andesitic and silicic tuffs, and volcaniclastic sedimentary rocks. Some beds grade from andesitic to silicic, and contemporaneous fallout from two sources is indicated. Several of the silicic beds contain chlorite- and epidote-rich fiamme in a laminated or massive, fine-grained silicic matrix. These fiamme probably represent pumice lapilli that collapsed during diagenesis and burial (Davis, 1989; Branney and Sparks, 1990). Though this mechanism of fiamme formation is best seen in the Pets Quarry GCR site, Sour Milk Gill is also a good place to examine such features, and to compare them with fiamme formed by welding of hot tuff, as seen in silicic eutaxitic ignimbrites of the Crinkle Tuffs exposed higher in the section.

In the Airy's Bridge Formation, the Cam Spout Tuff is well exposed on the south side of Sour Milk Gill (228 121). It is a spectacular cross-bedded tuff, 6 m thick, with abundant large accretionary lapilli and lapilli-impact structures and has been traced around the Scafell Caldera to Cam Spout in Eskdale and southwards to Wrynose (Branney and Kokelaar, 1994a). The turquoise, laminated Rest Gill Tuff is the lowest recognizable unit of the Crinkle Tuffs at Sour Milk Gill, and probably represents a particularly wet, large-scale phreatomagmatic eruption. Overlying the Rest Gill Tuff is a thick silicic ignimbrite with superb columnar polygonal cooling joints (at Hanging Stone; 228 120). Thin-sections show intense welding of the shards, with perlitic cracks and pseudomorphs after spherulites. Ignimbrites of the Crinkle Tuffs reach 500 m thick in this part of the Scafell Caldera.

Graphite, which gave rise to the Keswick pencil industry, can be found on disused spoil tips 500 m north of Sour Milk Gill (231 128). The mineral occurs in irregular pipe-like bodies within altered basic intrusions into the Whorneyside Formation (Firman, 1978a). The origin of the graphite is enigmatic, and may be related to underlying Skiddaw Group rocks (see the *Mineralization of Great Britain* GCR volume).

Interpretation

Rocks within the Whorneyside Formation in the Sour Milk Gill GCR site record the evolution of a dynamic, near-vent lake environment during a major explosive eruption accompanied by rapid differential volcanic subsidence. Beautifully preserved sedimentary structures record rapid ash fallout into shallow water, with sediment reworking by wave and current action, and the deposition of block- and ash-rich slurries. The spectacular soft-state deformation, Neptunian dykes, and dewatering structures resulted from rapid burial, shaking and tilting of watery lake sediment during the eruption. The accumulating ash and sediment at Sour Milk Gill were intruded by coeval andesitic magma, forming shallow, peperitic intrusions. Blocks, ash, sediment, and peperitic sills are all broadly of the same andesitic composition and may be co-magmatic. Primary volcanic aggradation by fallout from pyroclastic flows and from reworked equivalents of these produced about 69% of the succession, whereas secondary input from a variety of ash- and breccia-laden flows contributed the remaining 31% (Kokelaar and Branney, 1999). Sedimentation was demonstrably rapid, despite the deceptive fine grain-size and intricate stratification, because the 160 m-thick succession is a time correlative of *c.* 30 m of subaerial fallout ash to the south and was deposited during a single eruption, possibly lasting a few months or years. However, despite the rapid aggradation, water depth generally seems to have kept up with aggradation, because throughout the succession very small wave ripples indicate very shallow water and periodic emergence is indicated by polygonal mud cracks. The SE margin of the subsiding proximal basin was probably controlled by an active fault through Seathwaite (Kokelaar and Branney, 1999).

Elsewhere in the Lake District, the Whorneyside phreatomagmatic tuff is widely overlain by the Airy's Bridge Formation with an angular unconformity (see the Ray Crag and Crinkle Crags GCR site report) but at Sour Milk Gill the contact is conformable and gradational. Andesitic and silicic layers are interstratified, showing that the Airy's Bridge silicic eruption started before the andesitic Whorneyside eruption had ceased. Therefore, the widespread unconformity at the base of the Airy's Bridge Formation elsewhere must record a geologically instantaneous event, namely rapid caldera collapse, associated soft-state deformation and burial. This is in contrast to a protracted period of uplift and erosion. During the Airy's Bridge eruption the centre of subsidence shifted southwards with time from Sour Milk Gill, which became persistently emergent. This is illustrated by the Cam Spout Tuff (Figures 4.12, 4.17) which represents another important phreatomagmatic phase in the formation of the Scafell Caldera. Its presence at Sour Milk Gill shows that the area had become emergent, because pyroclastic surges are gaseous and too buoyant to invade standing water. This southward migration of subsidence means that the upper, subaerial part of the succession at Sour Milk Gill is thinner than ponded equivalents to the south. For example, the Bad Step Tuff is absent at Sour Milk Gill, but is over 400 m thick in Langdale (see the Langdale Pikes GCR site report), indicating the development of highly irregular caldera-floor topography as it subsided.

Conclusions

The Sour Milk Gill GCR site is internationally important because the exposed rocks were deposited in a volcanic lake situated near the vent of an exceptionally large-magnitude eruption caused by the explosive interaction of water and andesitic magma. The volcaniclastic rocks record particularly energetic explosions, rapid unsteady (pulsatory) ash fallout near to the vent, and contemporaneous reworking. Near-vent deposits of major phreatomagmatic eruptions at modern volcanoes, such as Lake Taal in the Philippines, and Lake Taupo in New Zealand, are mostly submerged and inaccessible. Therefore, this GCR site provides a rare view of the accumulation of these deposits, subsidence near to the vent, and how such watery basins are invaded by magma during the eruption to form stacks of sills. The site is particularly instructive because the volcanological context is well known from the continuity of outcrop around the Scafell Caldera, and the quality of the exposures allows individual beds to be traced for hundreds of metres.

Within the overlying Airy's Bridge Formation the Cam Spout Tuff at Sour Milk Gill is possibly the best example of a cross-bedded pyroclastic surge deposit in Britain, and the overlying welded tuffs show superb welding textures and polygonal columnar joints. Marked differences between the Sour Milk Gill succession and those of the Rosthwaite Fell and Ray Crag and Crinkle Crags GCR sites demonstrate that caldera subsidence can occur in a complex, piecemeal manner with adjacent fault blocks subsiding at different rates and being flooded at different times. This evidence has been highly influential in the way ideas about caldera collapse have developed in recent years.

ROSTHWAITE FELL (NY 258 122)

M. J. Branney

Introduction

Almost continuous exposure on the slopes of the Rosthwaite Fell GCR site, Borrowdale, provides a further section through the caldera-fill succession in the northern part of the Scafell Caldera (see the Ray Crag and Crinkle Crags GCR site report; Figures 4.12, 4.18). However, the site has been selected principally for two important aspects. Firstly, the pre-caldera lavas and an overlying ignimbrite are overlain by a pile of andesite sheets, which represents shallow-level ponding of andesite magma into accumulating ash in a proximal, subsiding volcanotectonic basin during the phreatomagmatic phase of the Whorneyside eruption. Secondly, post-caldera collapse magmatism is represented by the Rosthwaite Rhyolite, a coulée whose fault-controlled intrusive feeder is exposed in cross section. Silicic tuffs and ignimbrites of the Airy's Bridge and Lingmell formations, and caldera lake sedimentary rocks of the Seathwaite Fell

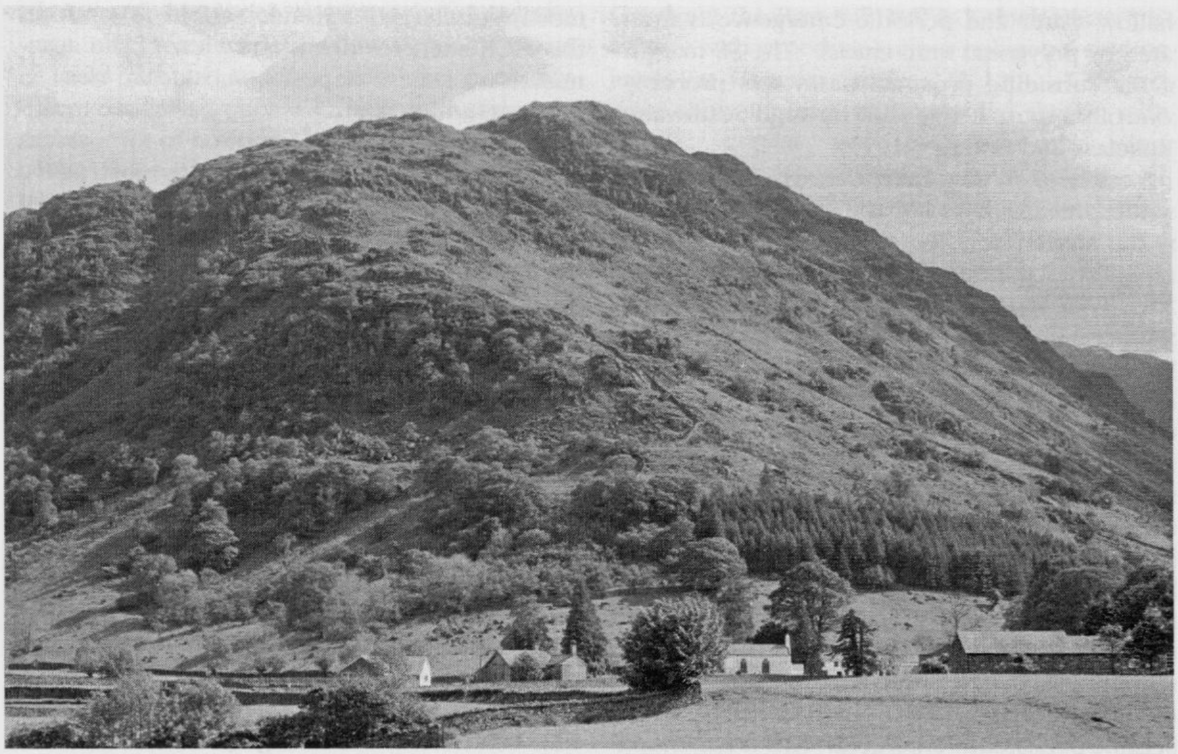


Figure 4.18 Rosthwaite Fell, from the village of Rosthwaite, Borrowdale. (Photo: D. Millward.)

Formation are also well displayed (Figure 4.19). The area has been described by Oliver (1954, 1961) and Millward (1976). The most recent accounts are by Davis (1989), Branney *et al.* (1993), Kneller *et al.* (1993b), Kneller and McConnell (1993) and Branney and Kokelaar (1994a); the resurvey associated with this work is included in the Geological Survey 1:50 000 Sheet 29 (1999). During the resurvey parts of the 'Birker Fell Andesite Group' of Oliver (1961) were re-assigned to the Lingcove Formation of Branney *et al.* (1990) and sills within the Whorneyside Formation.

Description

The lowest units exposed at Rosthwaite Fell are autobrecciated andesite sheets that pre-date the Scafell Caldera eruptions. They belong to the Lingcove Formation of Branney *et al.* (1990) and to the Birker Fell Formation of Petterson *et al.* (1992). These rocks are overlain by the Whorneyside ignimbrite, which was the first phase of the Whorneyside eruption and marks the start of the major explosive episode of the Scafell Caldera (Branney, 1991). The ignimbrite is coarser grained than elsewhere in the caldera (it contains abundant blocks) and this may indicate relative proximity to source. The ignimbrite varies abruptly in thickness, from 60–120 m, and this is thought to represent ponding in the underlying lava topography. The ignimbrite is overlain by more than 690 m of andesite sheets intercalated with thin beds of parallel-bedded andesitic tuff. This subaerial fallout tuff is phreatomagmatic and is interstratified with some debris-flow breccias and reworked layers. The andesite sheets are individually up to 380 m thick and have flow-banded and flow-folded central parts, and marginal autobreccias. Some are sills, and locally the upper contacts are peperitic. The origin of others is equivocal and lavas may be present. The Whorneyside Formation on Rosthwaite Fell is about 700 m thick, much thicker than on the south side of the Scafell Caldera (130 m).

The lower part of the Airy's Bridge Formation (Long Top Tuffs) comprises thin, bedded, welded silicic ignimbrites and subordinate pyroclastic surge and fall deposits. This part of the succession is thinner (75–120 m) than in the southern part of the caldera (over 200 m thick), and it thins further towards the NE (Kokelaar, in Branney *et al.*, 1993). By contrast, the upper

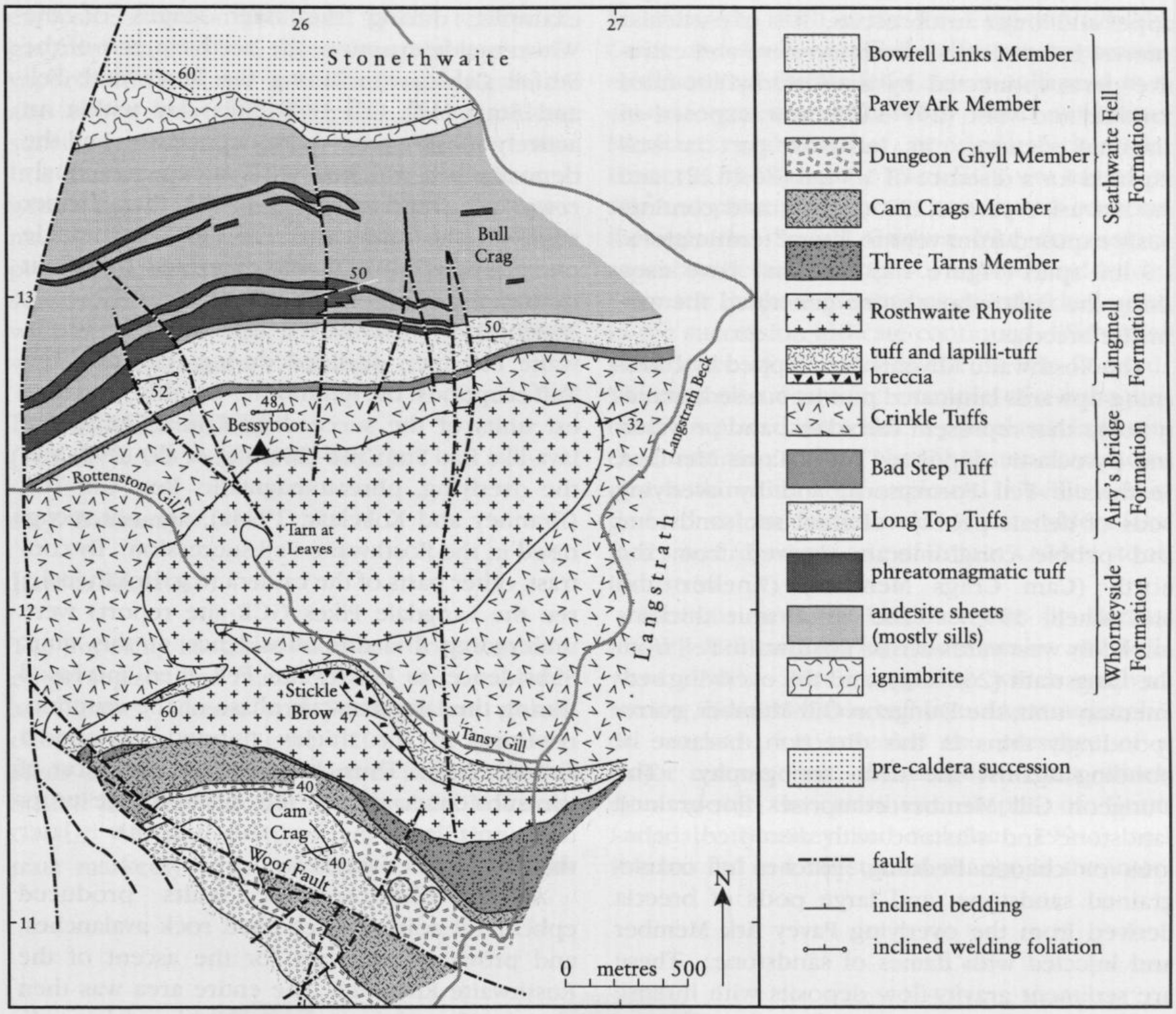


Figure 4.19 Map of Rosthwaite Fell, Borrowdale (based on mapping by B. P. Kokelaar, B. C. Kneller, N. Davies and M. J. Branney, for British Geological Survey).

member of the Airy's Bridge Formation (Crinkle Tuffs) is relatively thick on Rosthwaite Fell (*c.* 660 m). Ignimbrites of the Crinkle Tuffs are massive, intensely welded and commonly rheomorphic. Parataxitic fabrics, lineations and large-scale folds, all caused by rheomorphism, are best developed in the middle part of the Crinkle Tuffs. In a 10 m-wide zone adjacent to the Rosthwaite Rhyolite and a smaller rhyolite intrusion near Langstrath Beck, welding fabrics in the Crinkle Tuffs are deflected into concordance with the intrusive contacts. Columnar jointing is also present locally. The lava-like Bad Step Tuff (Branney *et al.,* 1992) is absent from the Rosthwaite Fell succession, but a massive eutaxitic lapilli-tuff, 3–15 m thick with a fine-grained top on Bessyboot (between 2543 1254 and 2679 1282) may represent a distal co-ignimbrite correlative (Branney *et al.,* 1993).

Subaerial, thinly stratified, clast-supported and locally eutaxitic, lapilli-tuffs and tuffs of the Lingmell Formation unconformably overlie the Crinkle Tuffs, and thicken westwards from the Langstrath towards Stickle Brow (261 118). A lens of clast-supported breccia containing blocks of welded Crinkle Tuffs thickens to 75 m towards Stickle Brow over a distance of about 300 m, possibly due to ponding in a half-graben, or formation of an apron of blocks along a volcanotectonic fault scarp (Kneller *et al.,* 1993b). The breccias are avalanche deposits, possibly with some pyroclastic breccias related to the extrusion of an overlying post-caldera-collapse rhyolite coulée (called the Rosthwaite Rhyolite; Millward, 1976; Davis, 1989). The rhyolite is crystal poor, flow-folded and perlitic, and has upper and lower autobreccias. It is of particular interest because it has both intrusive and extrusive parts connected by a short rhyolite-filled conduit and vent (257 118), now exposed in diagonal section. Its intrusive part is well exposed for a distance of 1.5 km (264 122), and the extrusive part is 130 m thick and continuously exposed from vent to lateral terminations, 1.9 km apart (Figure 4.19). It may have risen along the fault whose scarp generated the avalanche breccias.

The Rosthwaite Rhyolite is onlapped by coarsening-upwards laminated pumiceous sedimentary rocks that represent turbidites, and/or waterlaid pyroclastic deposits (Three Tarns Member, Seathwaite Fell Formation), and by overlying beds of deltaic pebbly volcaniclastic sandstone and pebble conglomerate derived from the north (Cam Crags Member) (Kneller and McConnell, 1993). The latter unit thickens markedly westwards across Rosthwaite Fell from the Langstrath (262 113), and the overlying sedimentary unit, the Dungeon Gill Member, correspondingly thins in this direction, because of ponding against the delta topography. The Dungeon Gill Member comprises fine-grained sandstone and siltstone with disrupted, nebulous or chaotic bedding, patches of coarse-grained sandstone, and large pods of breccia derived from the overlying Pavey Ark Member and injected with flames of sandstone. These are sediment gravity-flow deposits with intense soft-sediment disruption involving liquefaction, probably caused by sedimentary loading, slumping, and seismic shock. The overlying Pavey Ark Member, exposed on both sides of the WNW-trending fault along Woof Gill (258 112), is a breccia, *c.* 25 m thick, that grades up into 40 m of massive fine-grained sandstone (Raine, 1998). The breccia has layers containing abundant andesite blocks (2598 1090) whose shapes indicate that they were once hot and fluidal, as with basaltic volcanic bombs.

Interpretation

The volcanic succession of Rosthwaite Fell records the evolution of the northern part of the Scafell Caldera. It fits the generalized sequence of events inferred by Branney and Kokelaar (1994a; Figure 4.15). Marked differences in the succession between Rosthwaite Fell and other parts of the Scafell Caldera reflect proximities to former vents and very localized subsidence. For example, during the later stages of the Whorneyside eruption, the northern part of the Scafell Caldera (including the Rosthwaite Fell and Sour Milk Gill GCR sites) lay within an actively subsiding northern depocentre, and the deposits are thicker with more aqueously reworked components and sills than farther south in the caldera, where the Whorneyside phreatomagmatic tuff was deposited by fallout on to a flat subaerial ignimbrite plain (Branney, 1988b; 1991). However, subsidence at Rosthwaite Fell then declined during the Long Top Tuff eruptions: the ignimbrites are thin, and lowest units of the succeeding Crinkle Tuffs, the lava-like Bad Step Tuff (Branney et al., 1992) and the overlying, phreatomagmatic, Rest Gill Tuff (Branney and Kokelaar, 1994a), are not recognised in the Rosthwaite Fell succession. By contrast, other parts of the caldera (e.g. in Langdale; see the Langdale Pikes GCR site report) were undergoing dramatic subsidence at this time. Subsidence at Rosthwaite Fell then increased during the late climactic phase of the eruption, resulting in the thickly ponded uppermost Crinkle Tuffs. Thus, at Rosthwaite Fell most of the subsidence during the Airy's Bridge eruptions post-dated the Rest Gill Tuff; this is later than that farther south.

Active volcanotectonic faults produced ephemeral scarps which shed rock avalanches, and provided pathways for the ascent of the Rosthwaite Rhyolite. The entire area was then inundated and buried with caldera-lake sediments. A delta advanced from the north, and its toe was obstructed by the extant Rosthwaite Rhyolite coulée (Kneller and McConnell, 1993). The Pavey Ark Member is found extensively within the Scafell Caldera, and represents a catastrophic eruption-generated subaqueous gravity flow. It may be an intracaldera equivalent of spatter-rich co-ignimbrite lag breccias deposited from voluminous proximal pyroclastic flows, such as those that occur on rims of modern flooded explosive calderas, such as Santorini (Mellors and Sparks, 1991). If so, it is the only intracaldera example recorded worldwide.

Conclusions

This GCR site is important because is provides remarkably continuous exposure through the caldera-collapse cycle within the internationally significant Scafell Caldera. The site illustrates variations in the nature of alternations between explosive eruption produced by the release of gas from magma, and those driven by explosive vaporization of water on contact with magma. It also shows how different parts of the caldera subsided at different times and at different rates. It is thus complementary to the other GCR sites within the Scafell Caldera. Post-collapse magmatism is a principal feature of this site, which provides a rare and beautifully exposed cross section through the Rosthwaite Rhyolite along with its vent and feeder, centred on a fault that was active during the volcanism.

LANGDALE PIKES (NY 271 063–NY 300 082)

M. J. Branney

Introduction

The imposing Langdale Pikes have long fascinated geologists, and many crags in the area, such as Gimmer, Raven, and Whitegill are classic climbing localities (Figure 4.20). The Langdale Pikes GCR site illustrates further features of the Scafell Caldera of the Borrowdale Volcanic Group. Variations within the ignimbrites contrast markedly with correlatives in the neighbouring sites, such as the Ray Crag and Crinkle Crags, and Rosthwaite Fell GCR sites, to provide evidence that the Scafell Caldera collapsed in a chaotic, piecemeal fashion, with numerous localized graben that ponded thick tuffs. However, the Langdale Pikes GCR site has been selected principally for its continuous sections through the Scafell Caldera lake succession, arguably the best example of its kind worldwide. Dramatic thickness variations of individual units in the succession indicate continued differential subsidence of the caldera after it was flooded. There is also a unique example of a subaqueously emplaced intracaldera pyroclastic lag breccia containing scoria. Neolithic stone-axe factories within the area exploited silicified fine-grained volcaniclastic rocks of the caldera-lake facies and represent one of Britain's oldest stone industries.

Previous work in Langdale was by Hartley (1932), Millward (1976), and Moseley and Millward (1982). Recent mapping, which involved tracing distinctive thin tuff layers as stratigraphical markers, has revealed the presence of a major reverse fault, the Langdale Fault, which runs along the northern slopes of Great Langdale (Branney and Kokelaar, 1994a) and this has led to a substantial change in the inter-

Figure 4.20 The Langdale Pikes, viewed from the south. Welded ignimbrites within the Scafell Caldera form the lower crags and Gimmer Crag (top left of centre). Pyroclastic and sedimentary rocks of the caldera-lake succession are well exposed on Pike of Stickle (far left) and Harrison Stickle (right of centre). (Photo: D. Millward.)

pretation of the stratigraphy. The revised stratigraphy is simplified and thinner, because units near the valley floor are repeated up slope by the fault (Figures 4.12 and 4.21). Recent descriptions are given in Kokelaar *et al.* (1990), Branney *et al.* (1992), Kneller *et al.* (1993b), Kneller and McConnell (1993) and Branney and Kokelaar (1994a); these accounts are summarized in Millward *et al.* (in press) and the results are incorporated in the Geological Survey 1:50 000 Sheet 38 (1996).

Description

The Langdale Pikes GCR site extends from Grave Gill (277 065) to Whitegill Crag (298 071), and from the summits of Pike of Stickle (274 073), Harrison Stickle (298 073) and Pavey Ark (284 078) to the lowest exposures on the north side of Great Langdale. The lowest unit present is a single exposure of the Long Top Tuffs (Airy's Bridge Formation) at Grave Gill. More generally, the lowermost exposures are of the Bad Step Tuff, the basal unit of the Crinkle Tuffs (Figure 4.12), because this was thickly ponded in a small, ephemeral intracaldera graben in this part of Great Langdale. In this GCR site the Bad Step Tuff is over 400 m thick, but its base is not exposed.

The Bad Step Tuff is an ignimbrite that closely resembles a flow-folded rhyolite lava. Its pyroclastic origin is inferred on the basis of evidence elsewhere, where it is thinner (see the Ray Crag and Crinkle Crags GCR site report). Its uppermost 10 m are autobrecciated and interstices between the blocks are infilled with a fine-grained silicic tuff of possible co-ignimbrite ash-fall origin. It is overlain by the Rest Gill Tuff, a turquoise laminated silt- to fine sand-grade unit, which exceeds 3 m thick locally on the downthrow (south) side of the Langdale Fault, but is only a few centimetres thick on the upthrow side. This is overlain by massive eutaxitic ignimbrites of the Crinkle Tuffs, which locally display superb examples of small- and medium-scale rheomorphic folds. They thicken markedly towards the NW. Intercalated with them, and overlying them, are layers and lenses of breccia, up to 20 m thick, with angular, framework-supported blocks (up to 2 m across) of Bad Step Tuff and eutaxitic Crinkle Tuffs ignimbrites. These pass up into subaqueously deposited sedimentary rocks. The breccias overlying the uppermost ignimbrite of the Crinkle Tuffs, and the transitional beds into the lacustrine facies, have been grouped somewhat arbitrarily together as the Lingmell Formation (Figure 4.21).

The overlying lacustrine rocks belong to the Seathwaite Fell Formation (Figure 4.21). The total thickness of the caldera lake succession is approximately 540 m, but individual units vary dramatically in thickness. The lowest unit of this formation is the Three Tarns Member, which varies laterally from 3 m of ripple cross-laminated sandstone and siltstone above Whitegill Crag, to 80 m of laminated silicic mudstone, siltstone and fine-grained sandstone at Pike of Stickle. It commonly shows parallel and wavy lamination and slump structures. The mudstone is flinty, with a conchoidal fracture, and was worked for stone axes around Harrison Stickle and Pike of Stickle in Neolithic times. Epidote- and chlorite-rich fiamme are concentrated towards the tops of some beds and are inferred to represent pumice lapilli flattened during burial as a result of their diagenetic alteration to clays (cf. Branney and Sparks, 1990).

Two prominent dark bands seen in crags just below the summits of Pike of Stickle and Harrison Stickle form the Harrison Stickle Member (Figure 4.21). These are massive breccias and are 30 m thick on Harrison Stickle. They are overlain by the Dungeon Ghyll Member, about 60 m of intensely disturbed siltstone and epidotized sandstone (Kneller and McConnell, 1993). Some beds contain fiamme.

The succeeding Pavey Ark Member, named after Pavey Ark (285 078), comprises a massive, heterolithic coarse breccia, with an upwards-fining top that exhibits cross-bedding. The breccia is about 200 m thick in the east and thins westwards. South of the Langdale Fault it is about 10 m thick, and locally occurs as discontinuous pods. Its grain size varies gradationally. The breccia contains blocks of lapilli-tuff, rhyolite, sandstone, and concentrations of ragged amygdaloidal andesite clasts, whose embayed and folded shapes, sometimes draped and deformed around lithic clasts, indicate they were hot and plastic (Figure 4.22). These juvenile bombs commonly contain small angular rhyolite clasts. The Pavey Ark Member is overlain on Thunacar Knott by siltstone, sandstone and tuff of the upper part of the Seathwaite Fell Formation.

Interpretation

The dramatic thickness variations in the Crinkle

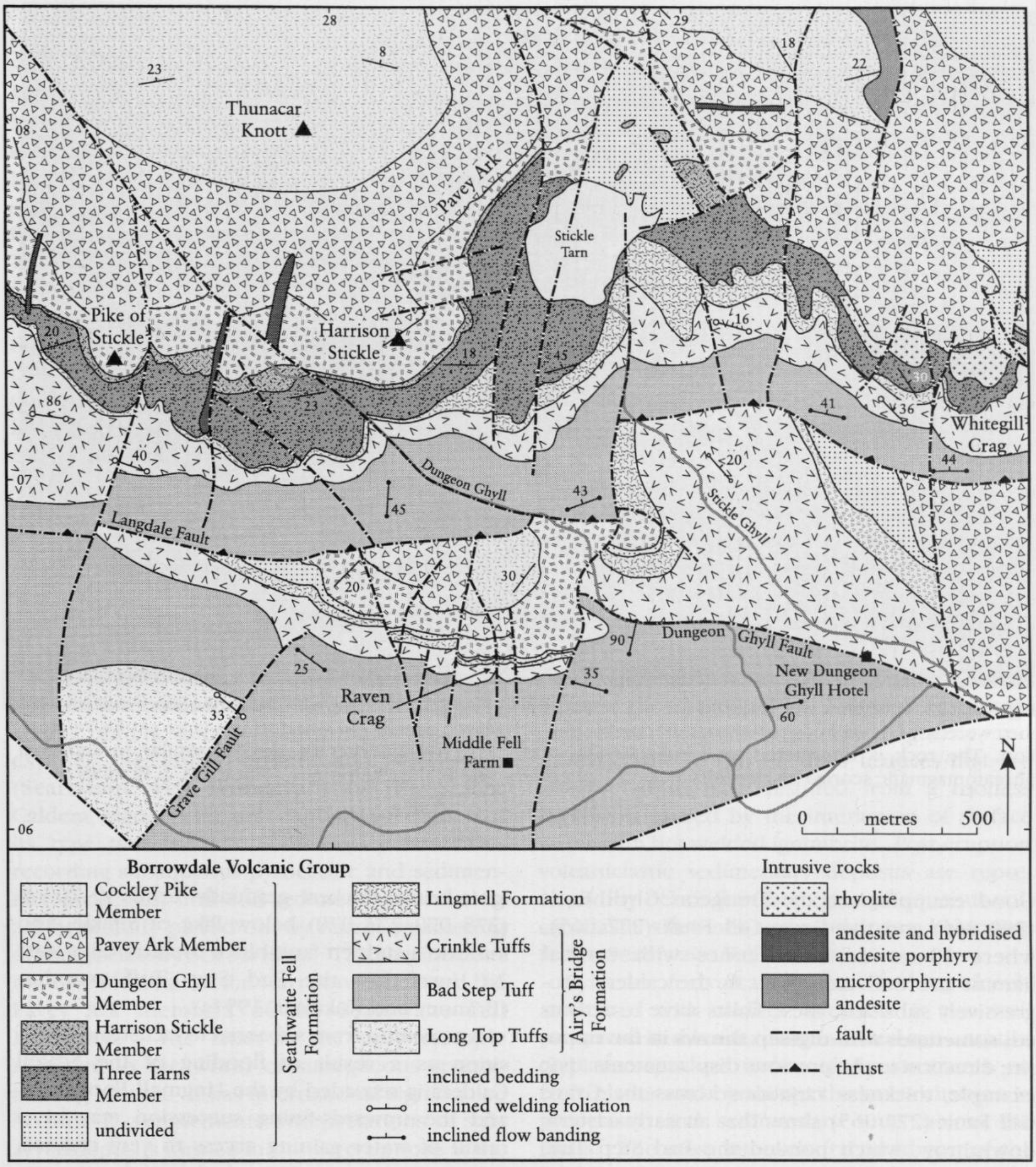


Figure 4.21 Map of the Langdale Pikes, Great Langdale (based on mapping by M. J. Branney, B. J. McConnell and B. C. Kneller, for British Geological Survey).

Tuffs ignimbrites and overlying caldera lake sedimentary rocks indicate a complex pattern of caldera subsidence, in which different areas subsided rapidly at different rates. The thickness of individual units in the caldera lake succession varies dramatically, indicating continued differential subsidence of the caldera after it was flooded. Volcanotectonic faults that bound the areas of differential subsidence are exposed in cross section. Zones of vertical and highly attenuated welding fabrics along the fault planes indicate ductile shear rather than brittle fracture and show that the faults moved when the ignimbrites were still hot (Branney and Kokelaar, 1994a).

Figure 4.22 Pavey Ark breccia from the top of Pavey Ark. Rag-shaped clasts with fluidal outlines indicate that they were hot bombs and spatter incorporated into a pyroclastic density current during a large explosive eruption. The rock is interpreted as a subaqueous scoria-rich co-ignimbrite lag breccia, similar to subaerial phreatomagmatic scoria-rich deposits around Taal caldera lake in the Philippines. (Photo: M. J. Branney.)

Good examples are the Dungeon Ghyll Fault (290 066) and the Grave Gill Fault (277 065), where 10 m-wide shear zones with vertical fiamme are well exposed. As the caldera progressively subsided, these faults were re-activated, sometimes with dip-slip throws in the opposite direction to the previous displacements. For example, thickness variations across the Grave Gill Fault (277 065) show that an early easterly downthrow, which ponded the Bad Step Tuff, was reversed during the next phase of the eruption (see Branney and Kokelaar, 1994a). The net displacement rate of these faults is much more rapid than has been recorded from tectonic faults. Contrasting successions on either side of the Langdale Fault indicate that it moved during caldera collapse and formed an unstable topographic scarp on the caldera floor that shed rock avalanches containing blocks over 2 m across. Elsewhere, strata geometries and thickness changes indicate that fault blocks rotated during caldera collapse. For example, well-exposed ignimbrites thicken gradually from 40–200 m (278 070–273 070) below Pike of Stickle, and indicate a sudden fault-block rotation of at least 20° just after the Bad Step Tuff eruption (Branney and Kokelaar, 1994a).

A transition from subaerial to lacustrine deposition as a result of flooding of the Scafell Caldera is recorded by the Lingmell Formation, and the upwards-fining succession may be a result of water gaining access to vent regions, causing an increase in explosivity (phreatomagmatism). The basal deposits of the Seathwaite Fell Formation are probably turbidites and ash falling directly into lake water, with wave and current reworking. The Harrison Stickle and Dungeon Ghyll members were rapidly emplaced as sediment-gravity flows, possibly derived from pyroclastic eruptions, and their soft-state disruption may record slumping, liquefaction due to sudden loading, and seismic shock. The Pavey Ark Member records another, larger volume sediment-gravity flow. Clasts within it closely resemble mafic scoria 'rags' found in association with proximal lag breccias at flooded calderas like Santorini, Greece (Mellors and Sparks, 1991). Away from the Langdale Pikes, the Pavey Ark Member fines upwards and laterally into sandstone and locally, eutaxitic tuff (Kneller and McConnell, 1993). The presence of hot magma spatter in the gravity flows suggests that the flows were generated by a pyroclastic eruption. The breccias probably represent intracaldera, lacustrine scoriaceous co-ignimbrite lag breccias from a major pyroclastic flow eruption that occurred in the flooded caldera. The fine-grained component could represent water-settled or trapped ash from the pyroclastic flows, or from the disturbed lake bed. This interpretation makes the Pavey Ark Member unique worldwide, because all other documented scoria-bearing co-ignimbrite lag breccias were subaerially deposited on caldera rims, and their intracaldera equivalents are inaccessible beneath caldera lakes.

Conclusions

The geology of the Langdale Pikes is remarkable because it records the final stages of collapse of a large caldera, and its inundation by water. It exposes the entire caldera lake succession (Seathwaite Fell Formation) of the Scafell Caldera, arguably the best-exposed succession of its type worldwide. Sedimentary structures recording subaqueous pyroclastic and sedimentary processes, and soft-sediment deformation are beautifully picked out by recent weathering of the glaciated rock surfaces. The site includes the type localities of the Harrison Stickle and the Pavey Ark members of the Seathwaite Fell Formation. The latter is the only example recorded in the world of subaqueous spatter-bearing breccia. It has international significance because it complements interpretations of subaerial deposits formed in similar eruptions at the Santorini, Taal, and Rabaul calderas.

Continuous sections through the uppermost caldera ignimbrites display superb plastic folds and both abrupt and gradual thickness variations, indicating fault-block subsidence and fault-block rotations within a subsiding caldera floor. The site was a fault-controlled depositional centre for the Bad Step Tuff, the ponding of which is localized within the Langdale part of the caldera. The site exposes internationally important examples of exhumed caldera-floor faults that have complex re-activation histories, and vertical welding fabrics along them. The Langdale Fault was originally a normal fault, active during the volcanic eruptions, but it was subsequently re-activated as a thrust, repeating the Langdale stratigraphy. It formed a scarp that shed avalanches, and the resultant coarse breccias exposed on the Langdale Pikes are among Britain's finest examples of caldera-collapse breccias.

SIDE PIKE (NY 293 053)

M. J. Branney

Introduction

Well-preserved subaerial pyroclastic successions in the ancient geological record are rare worldwide, largely because they are lost by erosion. The Side Pike GCR site contains possibly the best example in Britain of an ancient subaerial volcanic succession that exhibits in close association the three main categories of pyroclastic deposit: surge, flow and fallout deposits. It also records the three principal types of volcanic explosion, magmatic, phreatomagmatic and phreatic, and it also includes features that are interpreted to have resulted from a rootless explosion caused by the interaction of surface water with hot welded ignimbrite. Post-eruption volcaniclastic sedimentary deposits are represented by debris-flow breccias and aqueous volcaniclastic siltstones and sandstones, belonging to the Seathwaite Fell Formation.

Evidence for volcanotectonic faulting closely associated with caldera volcanism is also well preserved in this site. Large vertical syn-eruptive displacements are indicated by structures on fault planes and by abrupt thickness changes in pyroclastic and sedimentary units across the faults. The most intensely fractured part of the Scafell Caldera broke into blocks 10–1000 m in size; the resulting chaotic megabreccia covers an area of more than 5 km^2, and is known as the Side Pike Complex. Megabreccia is a characteristic feature of large calderas throughout the world (e.g. in the San Juan mountains, Colorado; Lipman, 1984), and represents caldera floor and/or wall rocks that fragmented as a result of caldera collapse. Side Pike forms a megablock, 500 m across, that lies near the eastern margin of the megabreccia.

The rocks of Side Pike were described first by

Branney (1988a, 1988b, 1990b), and Branney and Kokelaar (1994a).

Description

Side Pike is a small glaciated peak on the south side of Great Langdale. Strata generally dip about 25° to the east and are intensely faulted (Figure 4.23). The lowest unit (the Lingmoor Tuff; A of Figure 4.24) is exposed on the south and west flanks and consists of fine tuff with thin parallel stratification, low-angle cross-stratification and abundant accretionary lapilli, many of which have several concentric laminations. It was deposited by ash fallout and from pyroclastic surges (Figure 4.25a). Above it lie approximately 6 m of pale-weathered silicic tuffs in which stratification becomes more diffuse and subtle with height. They grade up into a pink, massive eutaxitic lapilli-tuff, which is about 30 m thick and is interpreted as a welded ignimbrite (B of Figure 4.24; Figure 4.25b). The size and degree of flattening of the fiamme change with height in the ignimbrite; the most flattened fiamme occur toward the centre. Locally (2902 0516), most of the thickness of the welded ignimbrite has been brecciated into angular, jigsaw-fitting blocks, with interstitial fine silicic tuff. The breccia grades laterally into coherent, unbrecciated ignimbrite, and the brecciation clearly occurred *in situ*. Where coherent, the ignimbrite is overlain by a 20 cm-thick layer of cream-coloured, very fine (formerly vitric) tuff with abundant 1 cm-diameter accretionary lapilli (C of Figure 4.24). The tuff layer exhibits little stratification, and probably records suspension fallout of fine ash after the passage of the pyroclastic density current that deposited the underlying ignimbrite (Branney 1988a, 1988b). It is therefore a 'co-ignimbrite ash-fall' deposit.

The vitric ash at the top of the ignimbrite forms a prominent grassy ledge. Above this lie 1–2 m of cross-bedded, fine to coarse tuff (D of Figure 4.24), in which sorting, undulatory sandwave cross-stratification and abundant accretionary lapilli indicate deposition from phreatomagmatic pyroclastic surges (Figure 4.25c). The surge deposit is incised by the irregular base of a monolithological breccia (E of Figure 4.24) that contains angular blocks of eutaxitic lapilli-tuff, closely similar to the underlying in-situ welded ignimbrite. The breccia's geometry, poor sorting and lack of internal organization indicate emplacement from a debris flow.

A diverse succession of fallout deposits, ignimbrites and aqueously deposited bedded volcaniclastic sedimentary rocks (F of Figure 4.24) overlies the debris-flow breccia. The sedimentary rocks exhibit spectacular soft-state deformation structures, and are locally overturned (e.g. at 2907 0537). Such localized and intense deformation is characteristic of the Side Pike Complex. Two amygdaloidal andesite sheets with marginal autobreccias lie within the bedded succession (Figure 4.23).

Between the andesite sheets lies the Lingmoor Tuff, a thinly bedded fine tuff with abundant accretionary lapilli (Figure 4.23). The tuff is also exposed in the saddle between Side Pike and Lingmoor Fell, and on the eastern end of Lingmoor Fell (2985 0510). It reaches 10 m thick and includes ash-fall layers with accretionary lapilli, and thicker, massive ignimbrite layers with matrix-supported fiamme. The top of the tuff is cut by gullies filled with sediment that contains locally derived intraclasts of accretionary lapilli-bearing Lingmoor Tuff. This indicates post-eruption reworking, possibly by ephemeral streams.

Vertical and deformed fiamme occur in eutaxitic lapilli-tuffs in the immediate vicinity of NNE-trending faults in the saddle between Side Pike and Lingmoor Fell (Figure 4.23). For example, vertical fiamme occur in a welded silicic ignimbrite, more than 40 cm thick, and plastered on to the faulted face of a massive andesite at 2938 0530. Many of the fiamme are sub-parallel to the fault plane and indicate fault displacement while the ignimbrite was still hot and able to shear in a ductile manner (Branney and Kokelaar, 1994a). The thickness of the massive silicic ignimbrite underlying the Seathwaite Fell Formation on Lingmoor Fell and Side Pike varies dramatically in thickness across the faults, as does the thicknesses of lacustrine sedimentary rocks between the ignimbrite and the Lingmoor Tuff (see cross section in Figure 4.23).

Interpretation

The lowest part of the succession in the GCR site illustrates the distinction between the varieties of pyroclastic deposit and also the characteristic types of volcanic eruption. The silicic tuff (B of Figure 4.24) that grades up from stratified into massive ignimbrite records the prolonged passage of a pyroclastic density current in which the

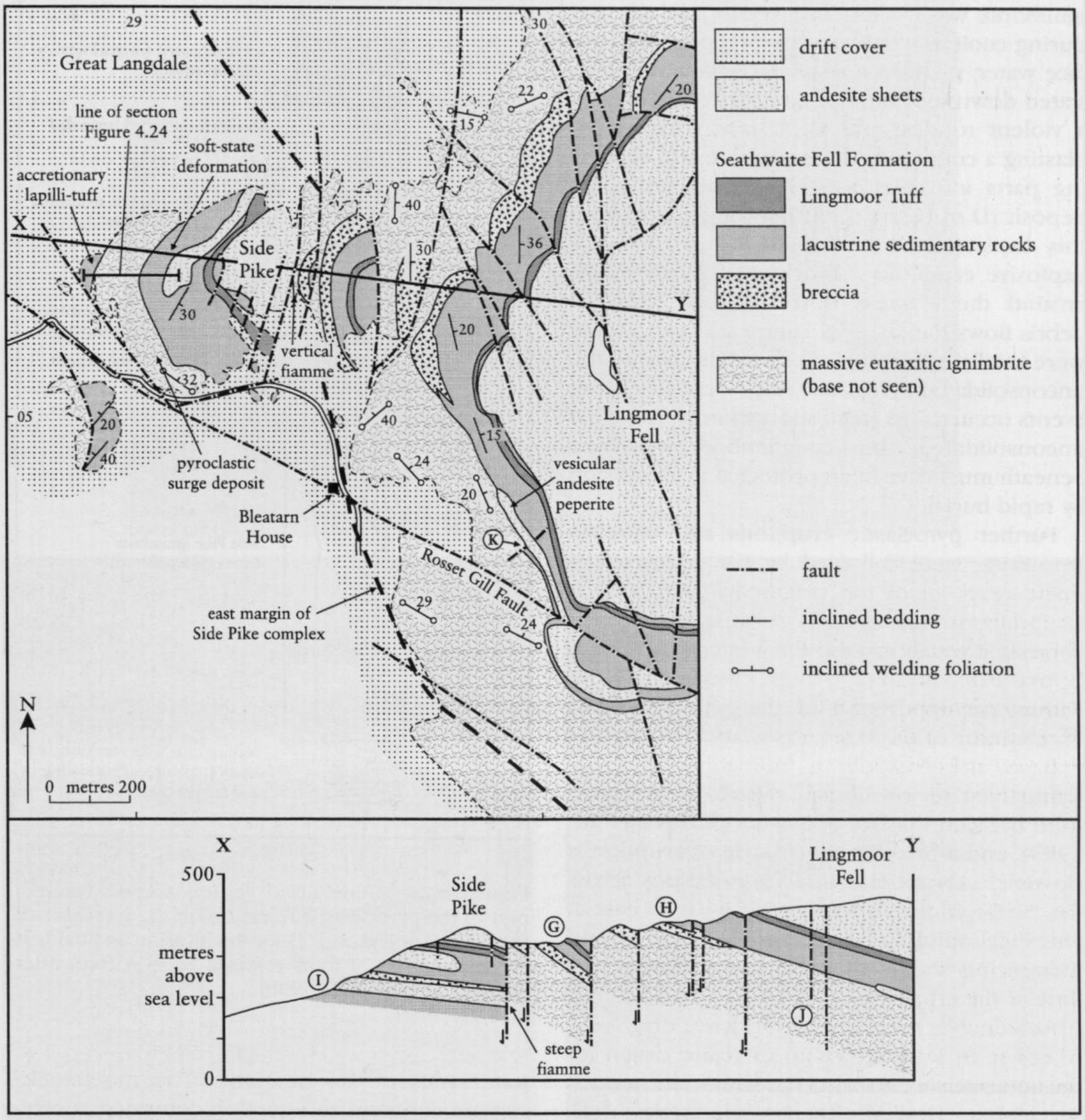


Figure 4.23 Map and true scale cross section (X–Y) of Side Pike, to show thickness changes across formerly eastward-downthrowing volcanotectonic faults, which have since been re-activated in the opposite sense. Note the change in thickness of lacustrine sedimentary rocks (between G and H) and of ignimbrite (between I and J), and the steep fabrics at two of the faults that record hot deformation of ignimbrite. A peperitic sill cuts a fault at K indicating that the fault pre-dates dewatering of the sediments. Localities G to K are described in the text. (Mapping by M. J. Branney and E. W. Johnson.)

concentration of particles increased with time. The eruption was magmatic and the welding indicates a high temperature. Gentle fallout of fine ash from a dilute co-ignimbrite ash cloud left in the wake of the density current gave rise to the thin co-ignimbrite ash-fall layer on the top of the ignimbrite (C of Figure 4.24). Co-ignimbrite clouds are known to loft high into the atmosphere, and it is probable that the thin vitric ash layer once covered an area of several hundreds of square kilometres. During and after its deposition, the underlying hot ignimbrite was undergoing welding compaction during cooling. Shortly after the eruption, surface water, possibly a small water-course, penetrated down into the hot ignimbrite and caused a violent rootless phreatic (steam) explosion, blasting a crater into the ignimbrite and shattering parts into blocks. The pyroclastic surge deposit (D of Figure 4.24) may be derived from this explosion or from similar contemporary explosive eruptions. Blocks of ballistic ejecta around the rootless vent sloughed away as debris flows (lahars; E of Figure 4.24) and these were locally deposited into channels cut into the unconsolidated pyroclastic surge deposit. These events occurred in rapid succession because the unconsolidated, thin co-ignimbrite ash layer beneath must have been protected from erosion by rapid burial.

Further pyroclastic eruptions and aqueous reworking were followed by the phreatomagmatic eruption of the Lingmoor Tuff. This is important stratigraphically because it has been correlated widely around the western part of the Borrowdale Volcanic Group outcrop. It lies within the upper part of the Seathwaite Fell Formation. The facies association resembles that of the Neapolitan Yellow Tuff of the Campanian region of Italy, which was erupted from beneath the Bay of Naples (Scarpati *et al.*, 1993), and a broadly similar style of eruption is possible. Abrupt lateral facies variations across the NNE-trending volcanotectonic faults east of Side Pike indicate that the faults were active and influencing the local palaeogeography at the time of the eruption.

At Side Pike there is little evidence diagnostic of either an intrusive or an extrusive origin for the andesite sheets that occur within the bedded succession. However, their stratigraphical positions coincide with two andesite sheets on Lingmoor Fell (Figure 4.23) where there is evidence that the lower one is a high-level peperitic sill indicating intrusion into a wet substrate (see the Pets Quarry GCR site report for details of the mechanisms of intrusion). It cuts a contemporaneous volcanotectonic fault (K on Figure 4.23) and has fluidized and vesiculated suprajacent bedded sediment (Branney and Suthren, 1988). The critical top contact of the upper andesite sheet is not exposed.

The precise origin of the large-scale brecciation of the Side Pike Complex is not known. There appears to have been more than one phase of early fracturing, characterized by soft-

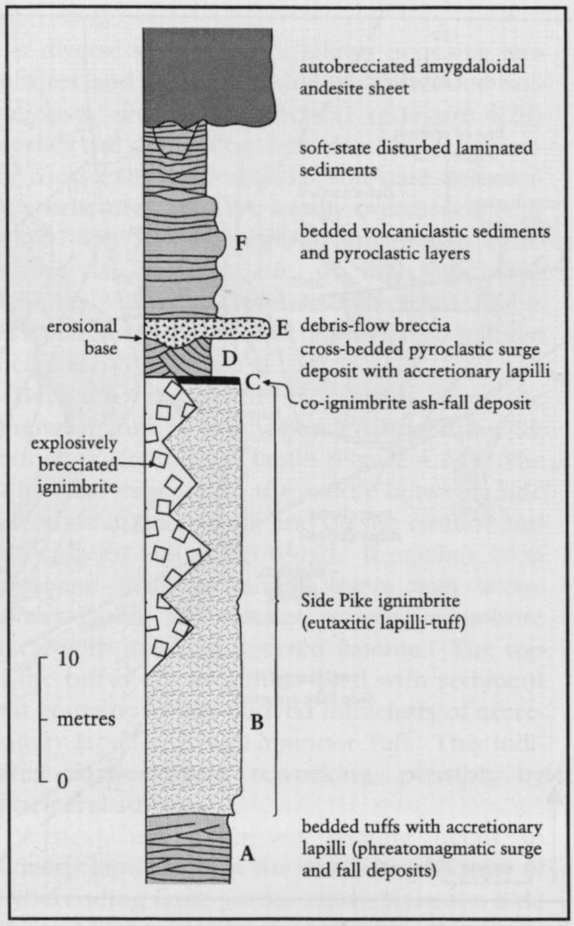


Figure 4.24 Generalized vertical section through part of the pyroclastic succession on the west side of Side Pike; see Figure 4.23 for the location and the text for explanation of units referred to as A to F. After Branney (1988b and 1990b).

state styles of deformation. The megablocks contain coherent to intensely deformed successions, some of which correlate with the Scafell caldera-floor and caldera-fill successions. However, several megablocks have 'exotic' volcanic sequences of unknown provenance, even though these may, in some cases, be correlated from one megablock to another (Branney, 1988b). The subaerial pyroclastic succession on Side Pike correlates with the successions seen in several other megablocks on Wrynose Fell, just to the SW, but this succession has not been recognized outside the Side Pike Complex; thus its precise stratigraphical position in the Borrowdale Volcanic Group remains uncertain. However, uppermost units in the Side Pike megablock are thought to correlate with the

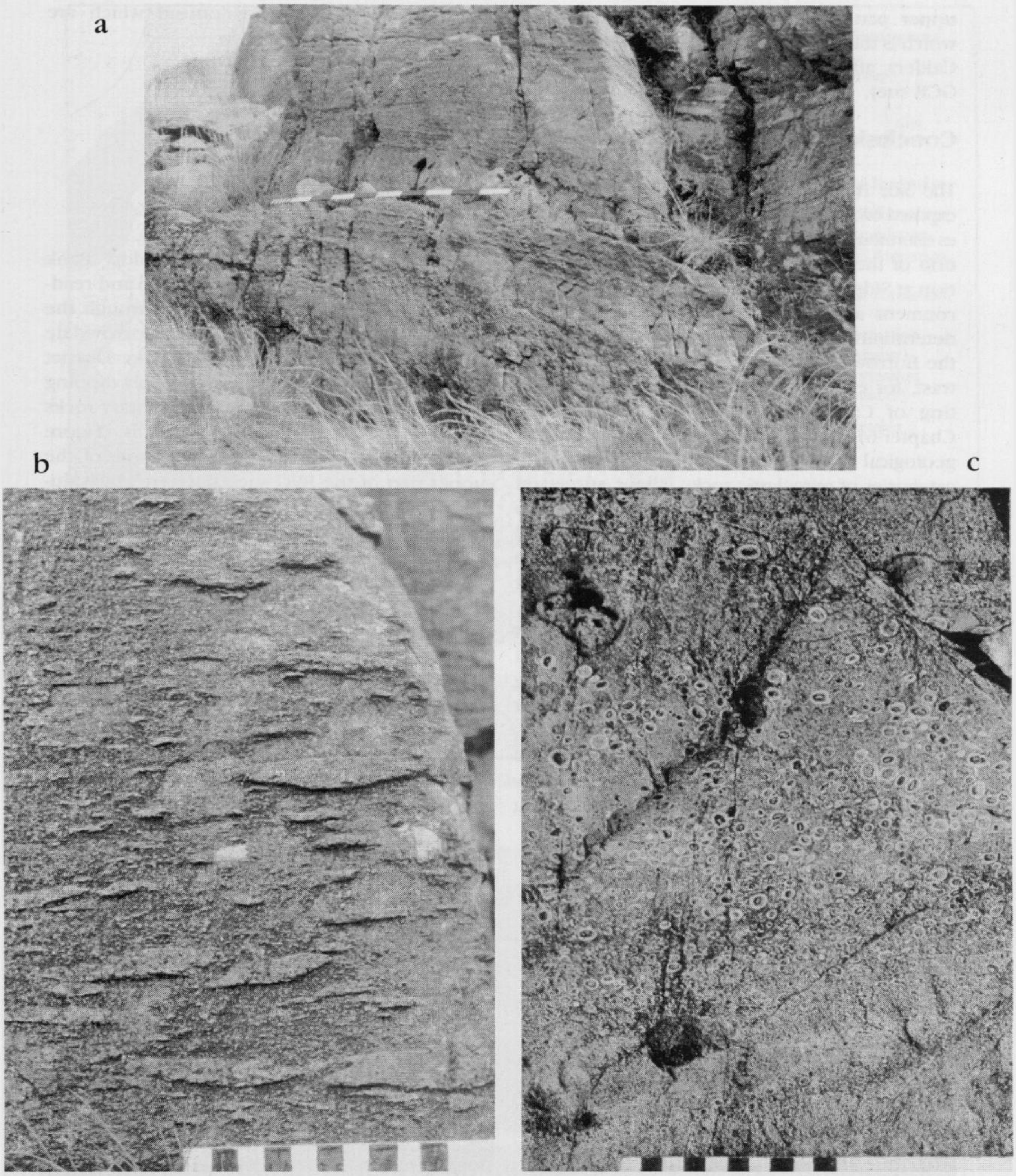


Figure 4.25 Subaerial pyroclastic rocks at Side Pike, Langdale: (a) Cross-bedded phreatomagmatic fallout and surge deposits, which underlie the Side Pike ignimbrite. (b) Rhyodacitic welded ignimbrite (the Side Pike ignimbrite). (c) Accretionary lapilli-tuff in pyroclastic surge deposit that overlies the Side Pike ignimbrite. (Photos: M. J. Branney.)

upper part of the Seathwaite Fell Formation, which is the record of a lake that filled the Scafell Caldera after it subsided (see Langdale Pikes GCR site).

Conclusions

The Side Pike GCR site is part of a breccia that is exposed over more than 5 km^2. The breccia comprises enormous blocks and is associated with the formation of the Scafell Caldera. The facies association at Side Pike is diagnostic of a subaerial environment and its discovery was influential in determining the overall non-marine character of the Borrowdale Volcanic Group. This is in contrast, for example, with the island volcano setting of Caradoc rocks in North Wales (see Chapter 6). Side Pike is a rare site in the ancient geological record that exhibits the three main categories of pyroclastic rock: fallout, surge and flow deposits in close association. It also includes superb, rare examples of an ash-fall deposit associated with ignimbrite and the record of rootless steam explosions that occurred shortly after an ignimbrite eruption, while the ash deposits were still hot. Though secondary explosions of this type are well known at modern volcanoes, such as following the recent ignimbrite eruptions of Mount St Helens (USA) and Mount Pinatubo (Philippines), such clear evidence from Lower Palaeozoic rocks is rare. Side Pike also provides excellent evidence for differential ground subsidence along faults generated during volcanism which are now exposed in cross section.

CONISTON (SD 290 978–303 990)

D. Millward

Introduction

North-west of Coniston village, Mouldry Bank and Long Crag provide a well-exposed and readily accessible example of a section through the uppermost formations of the Borrowdale Volcanic Group (BVG) in the SW Lake District (Figure 4.26). About 1800 m of steeply dipping pyroclastic and volcaniclastic sedimentary rocks are intruded by basaltic andesite sills (Figure 4.27). The section is a typical example of the upper part of the BVG succession in which fluvial and lacustrine volcaniclastic sedimentary deposits are intercalated with the products of voluminous silicic pyroclastic flow eruptions. These events post-date the Scafell Caldera ignimbrite succession. On Long Crag are spectacular examples of columnar joints in welded ignimbrite. Just to the west of this site are the Coniston Copper Mines, the location of a significant British mining industry during the last century, and represented in the 'Mineralogy of the Lake District' site network of the GCR. The sedimentary rocks are strongly cleaved and have been quarried extensively for slate.

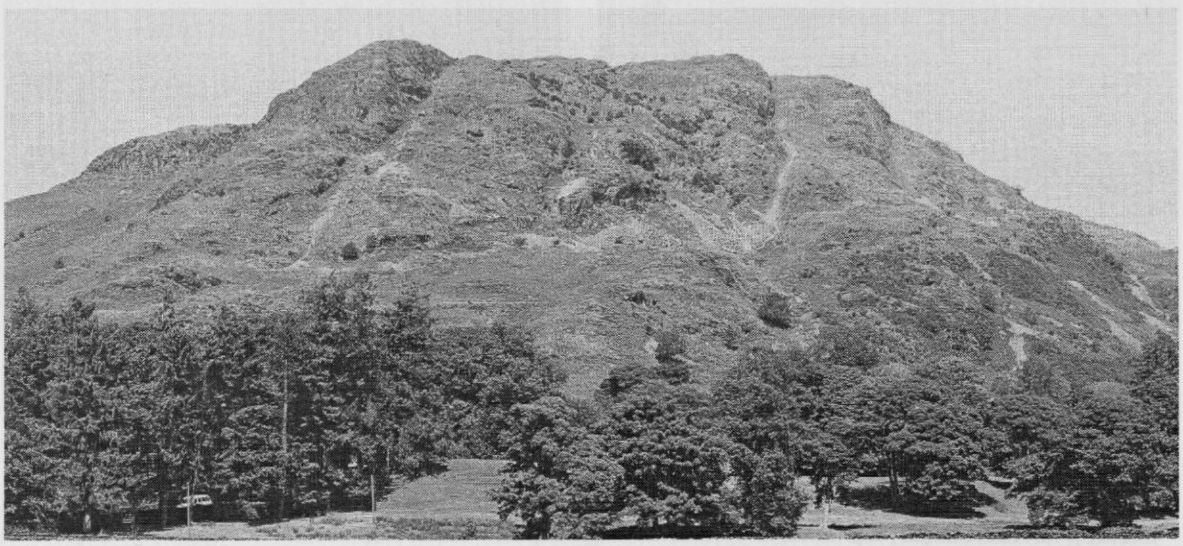


Figure 4.26 View of Long Crag from Coniston. The crags have been sculpted out of the ignimbrite of the Lincomb Tarns Formation and the low ground exposes Windermere Supergroup rocks, unconformably overlying the volcanic rocks. (Photo: D. Millward.)

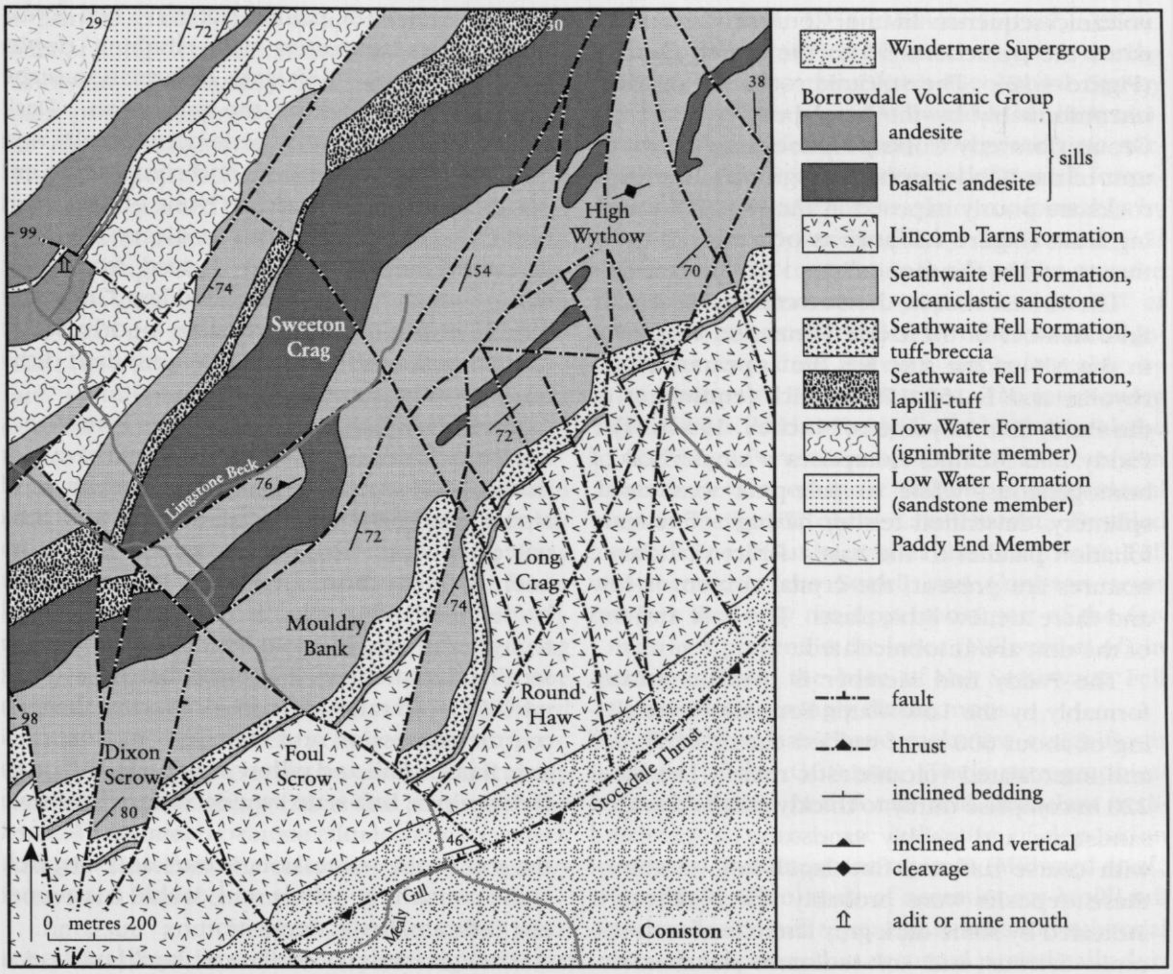


Figure 4.27 Map of the Coniston GCR site (based on BGS 1:50 000 Sheet 38, 1996).

The Coniston Fells were first mapped by the Geological Survey in 1882, but it was Mitchell (1940), who established the volcanic stratigraphy and structure of the area. The repetition of volcaniclastic sedimentary and pyroclastic rocks, both at Coniston and elsewhere in the BVG, was interpreted by Mitchell and others (e.g. Green, 1920) in the first half of the twentieth century as a set of tight folds with steeply dipping axial planes. This structural model for the BVG was subsequently abandoned by Mitchell (e.g. 1956) as studies of the sequence progressed. The GCR site description is based on work by Millward (1980), Millward *et al.* (in press) and the Geological Survey 1:50 000 Sheet 38 (1996). Re-interpretation of the stratigraphy and structure of the central Lake District has resulted in revision of the lithostratigraphical nomenclature from Mitchell (1940). His Upper Tilberthwaite Tuffs are divided between the Low Water and Seathwaite Fell formations; the Yewdale Bedded Tuffs become part of the Seathwaite Fell Formation; and the Yewdale Breccia is correlated with the Lincomb Tarns Formation of the central Lake District. The Wrengill Andesites are re-interpreted as sills (Branney and Suthren, 1988). Watson (1984) considered brecciated rocks at Colt Crag (280 980) to the west of the GCR site to lie within a possible vent for the BVG, but these rocks have been interpreted subsequently as autobrecciated andesite sills. Part of the area is covered by a field guide (Moseley, 1990).

Description

In the Coniston area the volcanic rocks dip steeply to the SE, within the steep limb of the monocline that is the principal structure of the area encompassing the uppermost BVG and Windermere Supergroup SW of Ambleside. The volcanic sequence in the Coniston area post-dates the pyroclastic fill to the Scafell Caldera (Figure 4.12). The volcanic rocks are overlain unconformably by the basal beds of the Dent Group (formerly Coniston Limestone and basal unit of the Windermere Supergroup), but these rocks are poorly exposed in the site. NE-trending faults (Figure 4.27) are associated with back-thrusts within the monocline.

The lowest unit in the succession, the Paddy End Member of the Lickle Formation crops out in the NW of the site, has the appearance of a rhyolite and is 150–170 m thick (equivalent to the Paddy End Rhyolite of Mitchell, 1940). The Paddy End Member comprises a single bed of homogeneous, white to pale-pink weathered, splintery, devitrified felsite, having a fine-scale foliation parallel to the base. Relict vitroclastic textures are present; the crystal content is low and there are few lithic clasts. The base and top of the unit are autobrecciated.

The Paddy End Member is overlain unconformably by the Low Water Formation, consisting of about 600 m of welded dacitic lapilli-tuff and intercalated volcaniclastic rocks. The basal 220 m comprise thinly to thickly parallel-bedded sandstone and pebbly sandstone, intercalated with coarse tuff and fine lapilli-tuff. Some of these deposits were probably water-laid, as is indicated by some dark-grey laminae of non-volcanic detritus and soft-sediment deformation. The succeeding two sheets of unbedded dacitic lapilli-tuff have a well-developed eutaxitic texture. Fiamme comprise up to 20% of the rock, which is also rich in angular, non-vesicular lithic lapilli. A lithic-rich basal zone up to 10 m thick contains blocks up to 70 cm across and forms a very poorly sorted, clast-supported breccia.

The Seathwaite Fell Formation mainly consists of up to 850 m of bedded volcaniclastic siltstone and sandstone locally intercalated with thin units of pyroclastic rock, particularly near the top of the formation. Though the base is conformable in the type area for the formation in the central Lake District (see the Langdale Pikes GCR site report), in the Coniston Fells an unconformity marks the base of the formation and the basal beds are probably markedly diachronous (Millward *et al.*, in press).

The basal lithofacies comprises up to 150 m of greenish-grey thinly bedded and laminated fine- and medium-grained sandstone and siltstone with sparse interbeds of pebbly coarse-grained sandstone intraclasts. Bedding and lamination are predominantly planar, but wavy bed forms, ripple cross-lamination and climbing ripples occur in places. Soft-state deformation structures occur throughout the succession. Dark-grey and brownish-grey beds occur locally near the base of the succession, and contain rare and poorly preserved acritarchs. None of the genera is demonstrably indigenous or diagnostic of age and they may have been derived from older marine strata, such as the Skiddaw Group. A 60–135 m-thick bed of massive poorly sorted dacitic lapilli-tuff, containing abundant lithic lapilli overlies these rocks.

Most of the formation in the area comprises a coarse lithofacies association of massive and thickly bedded, coarse-grained and pebbly sandstone intercalated with well-bedded and laminated, medium- to coarse-grained sandstone and minor siltstone. Bedding is generally poorly defined and predominantly planar, though trough and ripple cross-bedding are common locally. Sedimentary structures that are associated with rapid rates of deposition occur throughout the succession and include convolute laminae, flames, ball and pillow structures and dewatering pipes; soft-state syndepositional deformation and microfaults are also common. Towards the top of the succession, scours and channels, some containing pebble and cobble conglomerate, indicate fluvial deposition.

Though beds of tuff and lapilli-tuff occur throughout the formation, the most prominent that crops out throughout the GCR site is a coarse volcaniclastic rock, 25–80 m thick, occurring within the uppermost 150 m of the formation (Figure 4.27). Lithic blocks are concentrated in a basal 10 m-thick tuff-breccia, which passes gradationally upwards into overlying massive, lithic-rich eutaxitic lapilli-tuff; the uppermost 2 m are stratified. Characteristic pock marks on the rock surface show where pumice has been removed by weathering. This is overlain locally by the Glaramara Tuff, a white-weathered, splintery, bedded fine tuff, locally with accretionary lapilli and interbedded with thin beds of eutaxitic lapilli-tuff (see also the Side Pike GCR site report). Up to 30 m of parallel-laminated and cross-laminated, fine- to coarse-grained sandstone separates the tuff from the overlying Lincomb Tarns Formation.

The Lincomb Tarns Formation is a lithic-rich eutaxitic lapilli-tuff, up to 350 m thick. It is part of an extensive ignimbrite that crops out from the Coniston area, through Ambleside and

Grasmere to the Scafell area. It forms the rocky fells of Long Crag and Foul Scrow that overlook Coniston. Particularly conspicuous are abundant pink, angular, welded tuff and non-vesicular rhyolite fragments, commonly up to 2 cm. The lithic population is bimodal, also including many fine-grained basaltic andesite pyroclasts, in places with cumulose margins. Crystals, dominantly plagioclase with subordinate pseudomorphs after pyroxene and an opaque, form 4–14% of the rock. Fiamme are sparse to abundant (less than 5% to more than 35%) and some are identifiable pieces of long-tube pumice, altered to chlorite and an opaque mineral. A relict vitroclastic texture is preserved locally.

A characteristic feature of the formation in this area is columnar cooling joints, spectacularly displayed on Foul Scrow and Long Crag (Millward, 1980). At Long Crag at least two columnar zones have average column dimensions of 11 cm and 5.5 cm respectively. At Long Crag there is local small-scale variation in the inclination of the columns, which Millward attributed to unevenness in the cooling surfaces, possibly of separate eruptive units. The columnar zones have sharp bases and tops, and the column diameters remain constant along their length. However, the columnar zones have very restricted lateral extents.

Andesite and basaltic andesite sills were emplaced into the sedimentary rocks. These are variably massive to autobrecciated and locally intensely amygdaloidal. The contacts cut across bedding and the marginal breccias are intimately mixed with sandstone that in places is amygdaloidal.

Interpretation

Along with most of the early workers, Mitchell (1940) considered the volcaniclastic rocks in the BVG to be dominantly pyroclastic and the others, including the Paddy End Member and columnar-jointed parts of the Lincomb Tarns Formation to be lavas. Radical re-interpretation of the volcanic rocks of the Coniston area has occurred with the resurvey by the British Geological Survey, such that the new facies model shows a sequence dominated by volcaniclastic sedimentary deposits.

Abrupt lateral facies variations and faulting have caused many problems in correlating the volcanic succession across the Lake District and in particular between the Scafell and Coniston areas (Mitchell, 1956; Millward *et al.*, 1978). These problems have been resolved during recent work by the British Geological Survey (1:50 000 Sheet 38 and Millward *et al.*, in press). Within the Scafell Caldera, the pyroclastic succession of the Airy's Bridge and Lingmell formations (Figure 4.12) is overlain conformably by the dominantly sedimentary Seathwaite Fell Formation. By contrast, in the Coniston area the Airy's Bridge Formation (exposed to the NW of the GCR site) is succeeded by other welded ignimbrites and then overlain unconformably by the Seathwaite Fell Formation. The intervening ignimbrites of the Paddy End Member and the Low Water Formation are part of a succession that is developed more fully in a depositional centre in the SW of the Lake District. Detailed correlation of units within the Seathwaite Fell Formation in the Scafell and Coniston areas shows that only the uppermost part of the formation is present in the latter (Millward *et al.*, in press). Thus, the base of the Seathwaite Fell Formation is strongly diachronous.

Bedded volcaniclastic rocks are a significant feature of this GCR site. Their petrographical characteristics, bed forms and abundant sedimentary structures are indicative of deposition in fluvial and lacustrine regimes (Millward *et al.*, in press). Thin beds of accretionary lapilli-tuff and andesitic tuff represent small-scale subaerial ash-fall eruptions that occurred periodically during the major periods of relative quiescence represented by parts of the Low Water Formation and by most of the Seathwaite Fell Formation. However, the thin pyroclastic deposits are probably under-representative of the volcanic activity during deposition of the sedimentary formations, because of the poor preservation potential of unconsolidated tephra in the subaerial environment. Also, the presence of grey beds near the base of the Seathwaite Fell Formation, compared with the generally green colour of most of the sedimentary rocks is indicative of an influx of non-volcanic detritus from outside the volcanic basin, possibly associated with an interruption in the supply of volcanic detritus.

Interpretation of pyroclastic rocks in the Lake District underwent major change because of Oliver's (1954) recognition of many of the thick and extensive massive, eutaxitic lapilli-tuffs as ignimbrite. An extrusive origin for the Paddy End Member is confirmed from the basal field relationships and from the inclusion of felsite blocks in the overlying formations. The massive, lava-like felsite of the Coniston area passes south-westwards into welded lapilli-tuff (Millward *et al.*, in press), indicating that it is interpreted best as a rheomorphic ignimbrite. Mitchell (1940) mapped the columnar jointed parts of the Lincomb Tarns Formation (his Yewdale Breccia) as separate columnar lavas, but Millward (1980) demonstrated the pyroclastic nature of these rocks and included the columnar parts as part of a compound ignimbrite comprising multiple flow units. The bases to columnar zones may thus coincide with flow-unit boundaries, though there is little other evidence to support this.

The Wrengill Andesites were interpreted as lavas by Mitchell (1940). Branney and Suthren (1988) critically examined the contact zones of a number of andesite sheets at different levels in the BVG, including one NE of Church Beck. They included the intimate mixing of marginal andesite breccia with sandstone, sandstone amygdales in the andesite blocks and injection of sandstone into the andesite among extensive criteria diagnostic of intrusion of the andesite bodies into wet sediment. These andesite bodies also cut across the stratigraphy. Thus, there are no lavas within the succession seen in the GCR site.

Conclusions

The Coniston GCR site is an excellent and well-exposed representative example of the rocks deposited during the latest stages of mid-Ordovician volcanism in the Lake District. Fluvial and lacustrine sedimentation following major episodes of caldera collapse associated with the Scafell Caldera was interrupted by the emplacement of further voluminous dacitic ignimbrites from other centres. One such ignimbrite has spectacular developments of columnar cooling joints. Basaltic andesite and andesite magma was intruded into the water-saturated sediment pile.

PETS QUARRY (NY 392 073)

M. J. Branney

Introduction

Pets Quarry lies 300 m west of Kirkstone Pass. The quarry is cut into volcaniclastic sedimentary rocks of the Seathwaite Fell Formation (Figure 4.12) and the currently active faces are changeable. The excellent exposures of the contact relationships of a high-level sill illustrate features diagnostic of an intrusive origin into wet sediment. The sedimentary rocks are of considerable interest in their own right, because they record catastrophic syn-eruptive lacustrine sedimentation of hydroclasts by sustained turbidity currents. The site has been described and interpreted by Branney (1988b) and Branney and Sparks (1990).

The Borrowdale Volcanic Group (BVG) contains abundant sub-concordant igneous sheets throughout which, because they are readily distinguishable from volcaniclastic lithologies, have long been used as a basis for defining lithostratigraphical formations. However, it was established recently that sheets at many stratigraphical levels are intrusive (Branney and Suthren, 1988). The proportion of sills within the BVG remains unclear, but the recognition of sills that resemble blocky lavas has thrown into question the general practice of using the presence or absence of andesite sheets within local successions to define and to correlate lithostratigraphical units.

Early workers (e.g. Marr, 1916) compared andesite sheets in the BVG with modern autobrecciated lavas. Green (1913, 1915b) contended that many were sills, but subsequent workers (see Moseley and Millward, 1982 and references therein) concurred with the earlier interpretation, considering that the general concordance, brecciation, and lack of baking at upper contacts indicate an extrusive origin.

Recognition of high-level sills in the BVG (Branney and Suthren, 1988) followed work elsewhere (e.g. Kokelaar, 1982; Hanson and Schweickert, 1986), which had shown that sills intruded into wet sediment commonly do not bake the sedimentary host, for three reasons (Kokelaar, 1982). Firstly, steam generated at the magma contact insulates the host. Secondly, sediment immediately adjacent to the advancing margin of the intrusion is explosively disaggregated and excavated by steam, and is rapidly transported away along the magma–sediment contact in a fluidized state. And thirdly, an envelope of steam surrounding the invading magma can prevent the intrusion exerting directed stress on to the host to deform it. The removal of steam-fluidized sediment from the site of intrusion can give rise to strange contact geometries with an apparent 'space problem'. Well-preserved or only slightly deformed bedding in the sedimentary rock is sharply truncated by sill contacts, indicating that substantial volumes of host sediment have been removed with little trace. Contact relationships may be complicated further by differential burial compaction of bedding around irregular sill margins. This can produce structures that resemble draped or mantle bedding, similar to that which characterizes fall-out ash. Perhaps understandably, many such sills have been mistaken for lavas whose auto-brecciated tops have been draped or infilled, and then buried by ash or sediment. The origin of many andesite sheets in the BVG whose upper contacts are not particularly well exposed remains equivocal. The non-genetic term 'sheets' has been advocated for these (Branney and Suthren, 1988).

Description

The upper part of an irregularly shaped andesite sill is exposed in the quarry (Figure 4.28). The uppermost 8 m of the sill are brecciated; its base is not seen in the quarry, but is exposed a few metres below. Closely packed jigsaw-fit breccia grades upwards into an open framework-supported texture, and some of the uppermost blocks are apparently supported by sedimentary rock. At one place, loosely packed blocks form a 4 m-high vertical face at the top of the breccia. This is steeper than the repose angle, and it is unlikely that this could have been maintained without support of the sediment. However, there is no evidence that andesite debris from this body was reworked into the immediately adjacent sediments. Interstices in the breccia are occupied by andesitic sedimentary rock. In places this exhibits undisturbed lamination sub-parallel to the local dip. Elsewhere it comprises wispy discontinuous contorted laminations with soft-sediment shears and dislocations, or it is thoroughly homogenized. Bedding commonly abuts directly against the andesite blocks, though in many places there is a contact zone, 5 mm to 5 cm wide, of homogenized (formerly fluidized), pale, fine-grained sediment. Clouds of in-situ peperite, comprising locally spalled and quenched small hydroclasts set in homogenized sediment, occur adjacent to complex, highly irregular andesite block margins, particularly within zones of sediment between andesite blocks. Ellipsoidal chlorite amygdales up to 10 mm in diameter occur within the peperitic sedimentary matrix, and also occur in sediment that infills small vesicles in the andesite. There is ubiquitous penetration of fine-grained sediment into narrow fissures in the andesite and in the overlying sedimentary rocks. Many of the small vesicles in andesite adjacent to the fissures, or near the margins of the separated blocks, are completely filled with fine-grained sediment. However, vesicles in andesite away from the block margins contain no sediment.

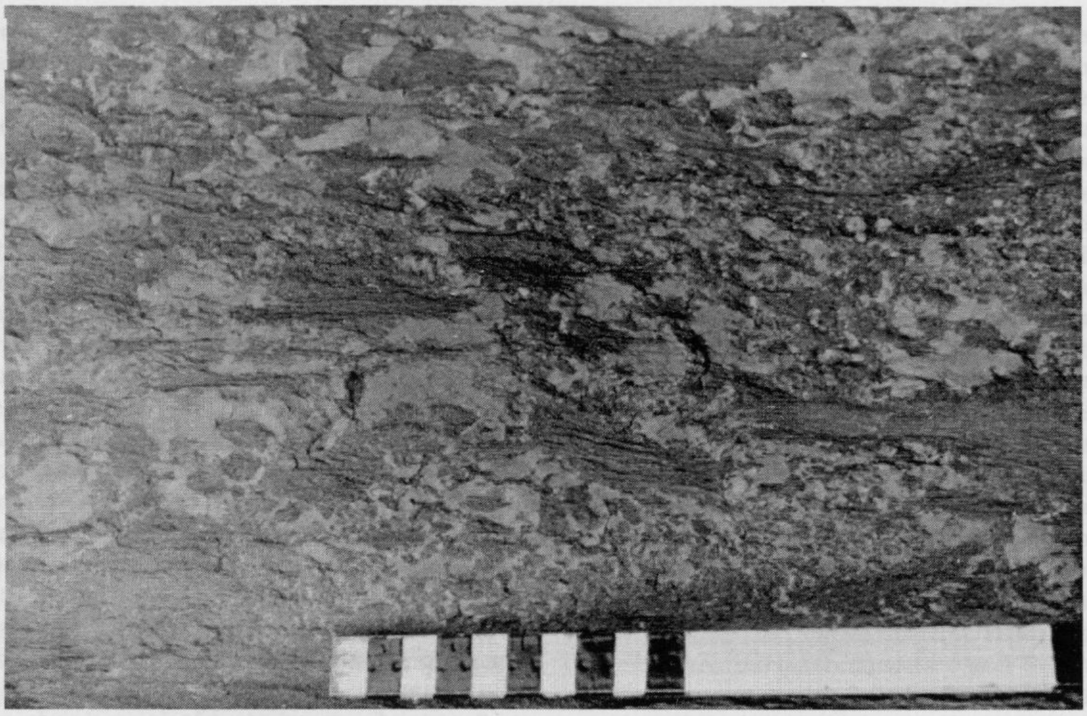
The host rocks are cleaved volcaniclastic siltstone, sandstone, and breccia, and bedding dips about 20° to the NE. Soft-state faults, and loading and dewatering structures are common. Some beds contain chloritic fiamme, whose shape indicates pre-cleavage burial compaction. Other beds contain angular blocks, up to 40 cm across, of vesicular andesite identical to those of the brecciated sill. The silty matrix of one bed contains vertical trails of carbonate-filled vesicles trails rising from andesite blocks, and carbonate-filled (steam?) geopetal cavities on the underside of andesite blocks.

Interpretation

The volcaniclastic rocks exposed in the quarry are correlated with the upper part of the Seathwaite Fell Formation, below the Glaramara Tuff (see Figure 4.23 and the Side Pike GCR site report). Chloritic fiamme in some of the volcaniclastic sedimentary rocks are interpreted to record waterlogged pumice or scoria clasts that compacted in subaqueous sediment by burial during diagenesis (Branney and Sparks, 1990). They cannot have formed by welding, because the rock is lacustrine and sedimentary rather than pyroclastic, and it could not have been hotter than 100°C. The sedimentary lithofacies include high-density turbidites and debris-flow deposits. The turbidites do not exhibit Bouma sequences. This is because the turbidity currents were prolonged and high density rather than dilute, single-surge events dominated by waning flow, and so they deposited disordered sequences of divisions, including variously graded, massive or stratified layers and scour-and-fill structures (Branney and Suthren, 1988; Branney *et al.*, 1990).

The following features seen in the andesite are diagnostic of high-level intrusion into wet sediment (Branney and Suthren, 1988):

a



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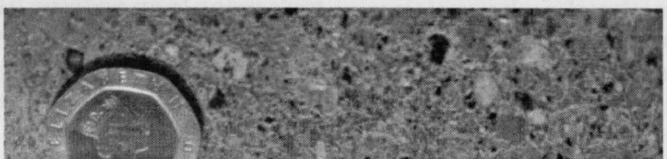

Figure 4.28 Details of peperitic andesite intrusions in the Seathwaite Fell Formation at Pets Quarry, Kirkstone Pass. (a) Andesite blocks have intruded lacustrine volcaniclastic sands and silts (pale coloured); patches of angular hydroclasts surround some block margins and sediment has been injected into cracks between the blocks. (b) Breccia formed by reworking of hot peperite on the lake floor. Geopetal sand partially infills vesicles later filled with carbonate (white) and chlorite (black) in the large andesite block. White carbonate beneath the block preserves a cavity that probably formed when the hot block heated water in the sediment matrix after its emplacement in a debris flow. The coin is 22 mm across. (Photos: M. J. Branney.)

1. Localized vesiculation of sediment above the andesite sheet suggests that the overlying sediment was already present at the time of andesite emplacement and was heated by the andesite.
2. Matrix-support of some andesite blocks also indicates that the sediment above the sheet was in place before the andesite was introduced.
3. Localized clouds of peperite around block margins indicate that block margins were undergoing in-situ hydroclastic decrepitation.
4. Sporadic, pale, faintly laminated fine-grained sediment rims around some andesite blocks are inferred to be remnants of sediment left behind after removal of disaggregated sediment by steam fluidization.
5. A lack of evidence of sedimentary reworking of the in-situ peperite is consistent with accumulation of the sediment before emplacement of the andesite.
6. Ubiquitous penetration of sediment into cracks indicates that the injected sediment was highly mobile, and probably water-fluidized and/or steam-fluidized.
7. Considering the volume of breccia, deformation that can be ascribed to sill emplacement is minimal. This suggests that sediment had been excavated by fluidization from sites now occupied by the andesite blocks.

Unequivocal criteria demonstrating intrusion, such as vesicles in the sedimentary rock, are not clearly visible where the upper intrusive contact of the sill in Pets Quarry is traced away from the fresh quarry face. It is also interesting that the diagnostic features do not occur everywhere along the contact. Movement of warm pore water through sediment is likely to have occurred as the intrusion cooled, and some of the host deformation may have been patchy post-emplacement dewatering and subsequent burial compaction. The andesite sill is autobrecciated in a similar manner to a block lava. This indicates that it had a similar rheology to a viscous block lava, and that it was in direct contact with only a steam carapace, so that the enclosing country rock was not able to exert significant mechanical constraint on the magma flow.

The sedimentary beds containing angular andesite blocks are also significant. The carbonate-filled geopetal cavities on the underside of blocks, and vesicles rising from their tops suggest that some of the andesite blocks remained sufficiently hot to vaporize the pore water of the debris-flow deposit after debris flow had ceased. The general facies association indicates that these beds were emplaced rapidly from unstable extrusive or unroofed parts of contemporaneous high-level sills that became emergent on the lake floor.

Conclusions

The Pets Quarry GCR site is perhaps the best and most accessible location in the Lake District that illustrates the processes of magma intrusion into near surface, wet sediment. Superb exposures show how sediment immediately adjacent to hot magma is mobilized by steam fluidization. Sediment only a little distance away from the contact is neither significantly heated nor disturbed, because a steam carapace around the invading magma effectively insulates the host, both mechanically and thermally, from the hot magma. The superficial similarity of this intrusion to a block-lava is instructive, and emphasizes the need for caution when interpreting the origin, and stratigraphical importance, of andesite sheets elsewhere.

The volcaniclastic sedimentary rocks show that sustained turbidity currents and debris flows may be generated during volcanic eruptions in lakes, and how the sedimentary facies produced in this way can be completely different from the much better-known sedimentary facies characteristic of non-volcanic turbidite settings. The site also exhibits pumice that has been flattened by low-temperature diagenesis and burial compaction. This closely resembles a lenticular type of disc (fiamme) formed in hot ignimbrite due to welding compaction (see also the Sour Milk Gill GCR site report). This alternative origin for such similar fragments is highly significant to the interpretation of volcaniclastic successions worldwide.

STOCKDALE BECK, LONGSLEDDALE (NY 477 049–493 060)

D. Millward

Introduction

Pyroclastic rocks and an enigmatic felsite seen within the Stockdale Beck, Longsleddale GCR site were probably erupted about 10 Ma after the end of the Borrowdale Volcanic Group (BVG) activity (Figure 4.29). These rocks are important in understanding the latest stages of Early Palaeozoic volcanism in northern England. Furthermore, the felsite is a good example of an extensive lava-like body of silicic composition with characteristics that have been taken to indicate that it is either a lava or a rheomorphic ignimbrite. The GCR site contains the type section of the Yarlside Volcanic Formation (Kneller *et al.*, 1994), the new name for the suite of rocks formerly known as the 'Yarlside Rhyolite' (Marr, 1892; Ingham *et al.*, 1978), 'Stockdale Rhyolite' (Gale *et al.*, 1979) and 'Stockdale Rhyolite Member' (Millward and Lawrence, 1985; Lawrence *et al.*, 1986). The formation is the thickest of several minor volcanic successions within the Dent Group of the Lake District and neighbouring northern Pennines. The felsite was distinguished first by Sedgwick (1836), but was described comprehensively only recently (Millward and Lawrence, 1985). The Rb-Sr isochron age of 421 ± 3 Ma has been used by Gale *et al.* (1979) to revise calibration of the Palaeozoic time-scale.

Description

The Yarlside Volcanic Formation crops out from Stile End (471 047) to near Shap Wells (577 096) in the eastern Lake District, but is in places extensively covered by Quaternary deposits. The formation overlies fine-grained sandstone and conglomerate of the Stile End Formation and locally, between the River Sprint and Stockdale Beck, volcanic rocks fill small-scale depressions in the top of the underlying formation (Figure 4.29). The uppermost beds of the Stile End Formation may have been thermally metamorphosed by the volcanic rocks (Ingham *et al.*, 1978). The volcanic rocks are overlain by a pebble-conglomerate comprising felsite fragments at the base of the Kirkley Bank Formation (formerly Applethwaite Member of Lawrence *et al.*, 1986). About 60 m of volcanic rocks are preserved near Sadgill Wood, thickening to 180 m east of Mere Crag around Stockdale Beck; the formation thins out west of the GCR site towards Stile End.

Most of the succession consists of a single bed of pink to pale-grey and greyish-green, splintery, massive to intensely fractured felsite that is platy jointed, flow-banded and flow-folded. It is high-silica rhyolite in composition. In Stockdale Beck, the type section, an almost completely exposed section through 180 m of felsitic rock comprises a single unit in which the lowest 45 m are strongly flow-folded and the uppermost

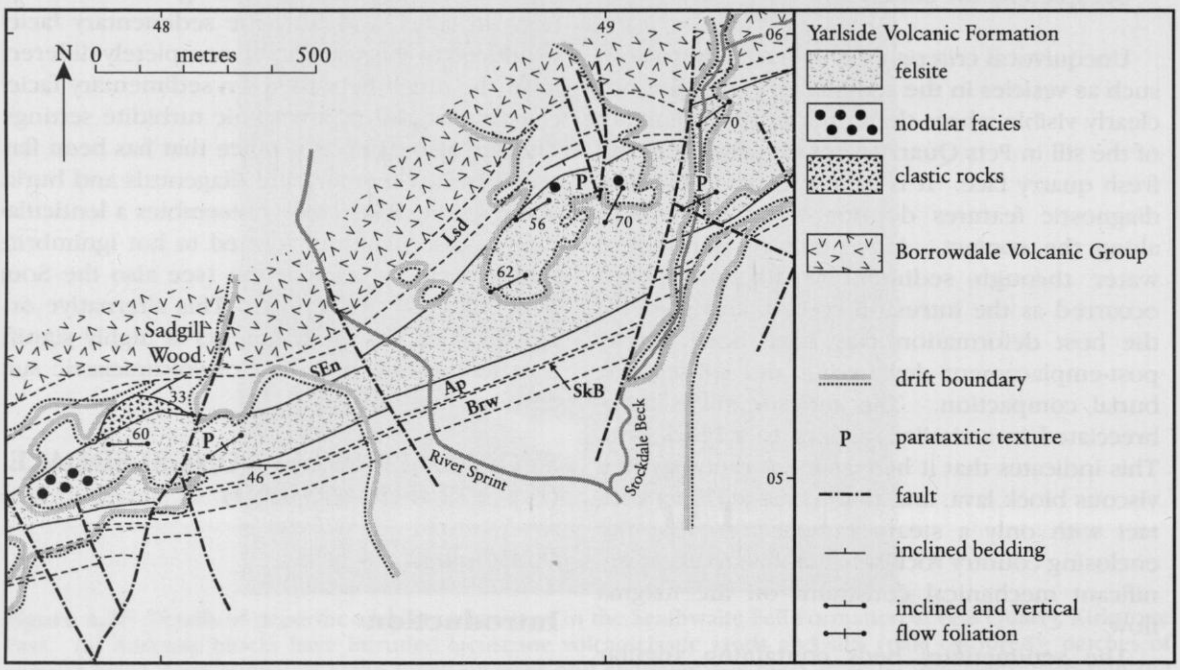

Figure 4.29 Map of the Stockdale Beck, Longsleddale GCR site (after Millward and Lawrence, 1985). Windermere Supergroup abbreviations: Ap, Kirkley Bank and Ashgill formations; Brw, Browgill Formation; Lsd, Longsleddale Member; SEn, Stile End Formation; SkB, Skelgill Formation.

30 m are massive with a vitroclastic-like texture and a devitrified fabric overprinting perlitic cracking; the central part comprises a mixture of these two facies. Abundant small, subangular to subrounded felsite clasts are present throughout. In the lower part of the unit, flow-banding is generally concordant with bedding in the underlying sedimentary rocks; in the upper part dips are generally steeper than the regional dip suggesting that ramp-like structures may be present. Flow folds range from small-scale open undulations to isoclinal, intrafolial structures, with amplitudes of a few centimetres to several metres. No autobreccia is associated with the felsitic rock.

The abundant small spherulites and perlitic cracking testify to the original glassy state. Devitrification textures include sutured fine-grained mosaics of quartz and feldspar, snowflake texture and elongate axiolitic structures. Recrystallization of the felsic rock has produced a fine- to medium-grained mosaic of anhedral quartz and subhedral albite. Locally the rock is riddled with small veins of quartz. Concentric perlitic cracks locally provide nucleation points for recrystallization, the fractures marked by chlorite and the intervening areas by partial, spherulite-like clusters of quartz and feldspar.

A nodular facies, referred to as 'agate-ball' structure by Sedgwick (1836), is well developed within the site (Figure 4.30). Most of the locally abundant nodules are single or intergrown expanded spherulites, up to 20 cm diameter, in which the original radiating quartz–feldspar fibres commonly have been ghosted by an overprinted snowflake texture. The central star-like cavities were filled subsequently by quartz with subordinate sericite and carbonate. The basal part of the unit west of Stockdale Beck (489 056) contains another type of nodule, up to 40 cm, without central cavities and with a concentric recrystallization fabric overprinting the undisturbed flow-banding.

In the west of the GCR site approximately 10 m of medium-bedded eutaxitic-textured lapilli-tuff occur at the base of the formation. Small lapilli-sized chloritized fiamme and pink felsite clasts occur within a vitroclastic matrix (Millward and Lawrence, 1985, fig. 4A). In the upper part of the formation in Stockdale Beck, and immediately to the east, grey, unbedded tuff contains subangular to subrounded felsite clasts set in a microcrystalline siliceous groundmass, which in places has a recrystallization fabric overprinting perlitic cracking. Strata up to 40 cm thick, local-

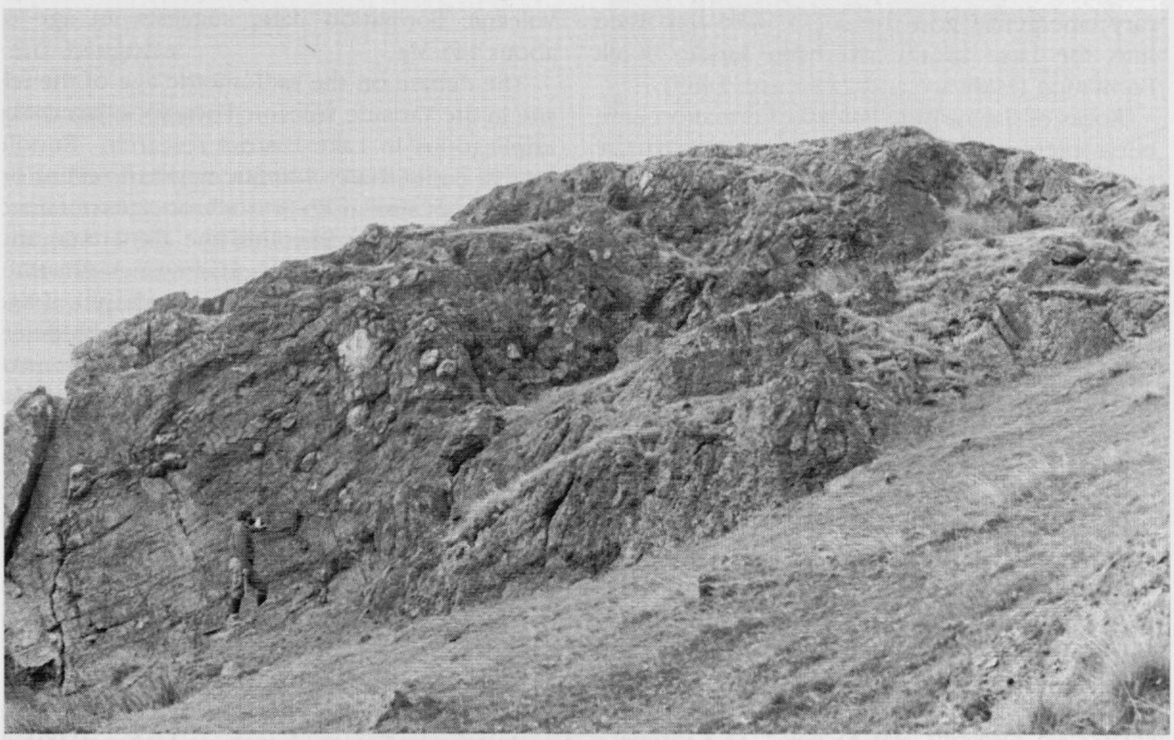

Figure 4.30 The Yarlside Volcanic Formation, approximately 450 m NW of Stockdale, showing flow-banded felsite containing large nodules formed by intense silicification. (Photo: BGS no. L3143.)

ly showing evidence of reworking, occur at the top of the formation east of Stockdale Beck (498 061) and comprise devitrified glass shards, fragments of pumice and sparse rhyolite clasts, but crystals are notably absent.

Interpretation

The Yarlside Volcanic Formation is probably the most voluminous post-BVG Lower Palaeozoic volcanic deposit in the Lake District and adjacent areas (Ingham *et al.*, 1978). The felsite is the only post-BVG lava-like volcanic rock, because the rest are clearly volcaniclastic. After the end of the major volcanic episode represented by the BVG, the Lake District underwent erosion and thermal subsidence that allowed clastic sediments derived from the volcanic massif to accumulate in a shore-face or beach environment, and this gave way subsequently to shallow-water carbonate shelf conditions. The similar outcrop distributions of the Yarlside Volcanic Formation and the underlying Stile End Formation suggest that they filled a coastal embayment (Kneller *et al.*, 1994). Rocks of the Yarlside Volcanic Formation were erupted into this environment, probably from a source to the south of the outcrop (Ingham *et al.*, 1978). Eruption of the felsite probably caused temporary emergence and the rocks were reworked into the base of the overlying Kirkley Bank Formation (Millward and Lawrence, 1985).

Rocks of the Yarlside Volcanic Formation have been interpreted in most accounts as extrusive and probably lava (Rutley, 1885a; Green, 1915b; Marr, 1916; Mitchell, 1934, 1956; Gale *et al.*, 1979). Gale *et al.* (1979) interpreted the three separately exposed parts of the outcrop as evidence for three lavas. However, Millward and Lawrence (1985) proved by detailed mapping that a single continuous outcrop is present. They described characteristics of the felsite that, in their opinion, are not typical of felsic lava. These include the facies association with thin pyroclastic beds in a marine and otherwise nonvolcanic environment, the absence of autobreccia, and the local presence of welded-tuff-like textures. They suggested that the felsite is interpreted best as a rheomorphic ignimbrite. During the last ten years there has been considerable debate about whether lava-like felsic bodies elsewhere are rheomorphic ignimbrites or true lavas (see Manley, 1996). The Bad Step Tuff in the BVG of the central Lake District described by Branney *et al.* (1992) is an excellent example of a lava-like ignimbrite (see the Ray Crag and Crinkle Crags GCR site report). However, textures seen in the felsite of the Yarlside Volcanic Formation have been described from probable lavas by Manley (1996), casting doubt on the interpretation by Millward and Lawrence (1985) and it remains possible that the felsite is an extensive lava.

The probable short time span represented by the volcanic episode and the close biostratigraphical control from fossiliferous beds above and below make the felsite a potential control point for calibration of the geological time-scale. Gale *et al.* (1979) used the Rb-Sr isochron age of 421 ± 3 Ma for the felsite as the date for the Ashgill. However, the same numerical age was obtained subsequently for the Laidlaw Volcanics near Canberra, Australia, which are also well constrained biostratigraphically, as early Ludlow (Wyborn *et al.*, 1982). Compston *et al.* (1982) re-examined the data presented by Gale *et al.* (1979) and concluded that emplacement of the felsite took place at least 430 Ma ago and that there was a net loss of Sr during hydrothermal circulation at around 412 Ma. The biostratigraphical age for the Yarlside Volcanic Formation is unequivocal and the time-scale of Harland *et al.* (1990), which does not use the Yarlside Volcanic Formation date, suggests an age of about 445 Ma.

The debate on the radiometric age of the felsite in the Yarlside Volcanic Formation has wider implications in Lake District research. Rundle (1979) defined a *c.* 420 Ma magmatic event on the basis of similar Rb-Sr isochron ages obtained for the Stockdale Rhyolite, the Ennerdale and Carrock granites, and the Harestones Rhyolite. In addition to the earlier biostratigraphical age for the Yarlside Volcanic Formation, U-Pb determinations on zircons from the Ennerdale intrusion have indicated a Caradoc age (452 ± 4 Ma, Hughes *et al.*, 1996), considerably older than its Rb-Sr date. Other dating methods have not yet been applied to the Carrock microgranite nor to the Harestones Rhyolite, but it seems unlikely that the Rb-Sr dates for these represent the age of intrusion. If the *c.* 420 Ma date is not the age of emplacement then what is the significance of this early Ludlow event? Hughes *et al.* (1996) suggested that resetting may be related to water–rock interaction caused by tectonic events at the onset of basin inversion which was associated with foreland basin and mountain front development in the Lake District upon closure of the Iapetus Ocean (Kneller *et al.*, 1993a).

Conclusions

The Stockdale Beck, Longsleddale GCR site contains the type section of the Yarlside Volcanic Formation, which comprises an extensive lava-like felsite and locally preserved pyroclastic and reworked pyroclastic rocks that were erupted about 10 Ma after the main phase of volcanism in the Lake District had ceased. These rocks were erupted into a shallow-marine environment, probably causing emergence locally. Lava and very intensely welded ignimbrite are possible interpretations of these rocks. The site is important because it contains the only Early Palaeozoic example of a lava-like felsite that post-dates the BVG. The felsite is also probably the most voluminous volcanic rock that post-dates the BVG. The intercalation of the felsite within a biostratigraphically well-constrained marine sedimentary succession gives this site potential value for the calibration of the geological time-scale.

BRAMCRAG QUARRY (NY 320 220)

S.C. Loughlin

Introduction

The Threlkeld microgranite is exposed in three main outcrops about 4 km east of Keswick (Figure 4.31). The outcrops on Low Rigg, Threlkeld Knotts and in Bramcrag Quarry are interpreted to represent a single irregular laccolith (Firman, 1978b). Prior to the excavation of Bramcrag Quarry in the early 1970s, the age and relationship of the Threlkeld microgranite to the Ordovician country rocks was difficult to ascertain (Hadfield and Whiteside, 1936; Rastall, 1940). Wadge (1972) suggested that the microgranite was emplaced prior to deposition of the Borrowdale Volcanic Group (BVG). However, the section exposed in Bramcrag Quarry clearly shows that the Threlkeld microgranite cuts both the Skiddaw Group and the lowest parts of the BVG. The petrography and geochemistry of the Threlkeld microgranite were described by Caunt (1984) who proposed that assimilation of Skiddaw Group material facilitated the low-pressure crystallization of garnet. The Threlkeld microgranite is now thought to be a high-level intrusion, contemporaneous with the thick succession of ignimbrites in the upper part of the BVG, though this theory is not entirely supported by isotopic dating (Wadge *et al.*, 1974; Rundle, 1981, 1992).

The Bramcrag Quarry GCR site is one of the best exposures of the Threlkeld microgranite and thus provides critical evidence for the timing of mid-Ordovician intrusive activity in the Lake District. In addition, Bramcrag Quarry illustrates the unconformable relationship between the Skiddaw Group and the overlying BVG (Figure 4.32).

Description

The Threlkeld microgranite, previously referred to as 'adamellite', is medium grained, light-grey and contains abundant feldspar phenocrysts (up to 5 mm in size) together with striking rounded

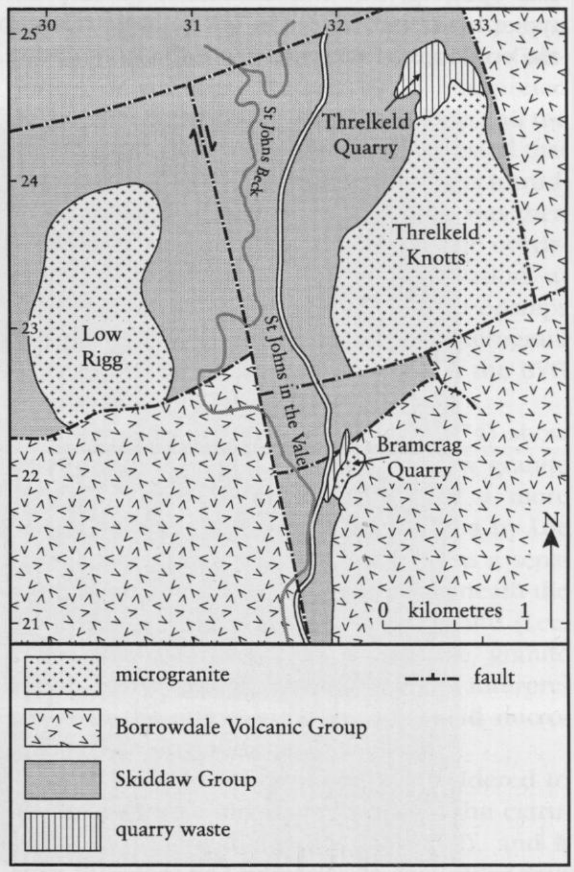

Figure 4.31 Map of the Threlkeld microgranite showing the location of Bramcrag Quarry.

quartz crystals. The feldspar phenocrysts are predominantly euhedral to subhedral albite with some pink orthoclase; they show no preferred orientation and may form glomeroporphyritic clusters. The feldspar phenocrysts show varying degrees of alteration to sericite, calcite, chlorite and quartz. Subhedral, elongate chlorite pseudomorphs intergrown with iron oxides may be after amphibole (Campbell, 1995) or biotite (Caunt, 1984). Sporadic anhedral garnet with ragged margins is also present. The groundmass is mainly composed of fine-grained granular quartz and sericitized plagioclase with some iron oxide and elongate chlorite pseudomorphs, perhaps after amphibole; accessory minerals include zircon and apatite.

The upper, sub-horizontal contact of the microgranite is exposed high along an inaccessible, worked face in the eastern part of the quarry, where it is overlain by mudstone, siltstone and tuffaceous sandstone belonging to the lowest part of the BVG (Figure 4.32). The sedimentary rocks are weakly hornfelsed and show thermal spotting, but this contact metamorphism typically extends for only a few centimetres from the contact and rarely to more than one metre. The microgranite has narrow chilled margins (less than 1 cm) from which phenocrysts are absent. The contact is generally sharp and planar; in the northern part of the quarry, a tongue of microgranite has penetrated the overlying sedimentary rocks with clear discordance. Debris on the quarry floor illustrates this type of intrusive relationship; there are also blocks of distinctive pyroxene-phyric basic lavas from higher levels in the BVG.

In the southern part of the quarry, the microgranite contact with the BVG dips at 5–10° to the SE. Some slickensided quartz veining can be seen along the contact suggesting that shearing has occurred. There is also some evidence that minor shearing occurred within the microgranite. Stepped slickensides and quartz slickencrysts found on selected joints within the microgranite indicate an oblique dextral-reverse movement (Campbell, 1995).

At the southern end of Bramcrag Quarry, a near-vertical intrusive contact of the microgranite cuts through the dark-grey mudstone and siltstone of the Skiddaw Group. Several metres above the Skiddaw Group rocks, which dip steeply to the SW, are sub-horizontal volcaniclas-

Figure 4.32 Bramcrag Quarry: the Threlkeld microgranite is overlain by lavas and volcaniclastic sedimentary rocks of the basal part of the Borrowdale Volcanic Group. The contact slopes from top right to lower left. (Photo: BGS no. L2041.)

tic sedimentary rocks and lavas of the BVG. Unfortunately, the plane of the unconformity is obscured by scree.

Xenoliths of Skiddaw Group lithologies are common, particularly near the margins of the Threlkeld microgranite, and range in size from a few millimetres to over one metre in diameter. These xenoliths are commonly spotted by contact metamorphism and some show intense folding within them (Rastall, 1940). Rare xenoliths of BVG rocks are also present. A near-vertical ENE-trending cleavage occurs throughout the quarry and post-dates the microgranite.

Interpretation

Hadfield and Whiteside (1936) reported whole-rock geochemical analyses on the Threlkeld microgranite which showed that, despite the abundance of xenoliths in certain places, the overall composition of the granite seemed to be largely unaffected by their assimilation. The compositional uniformity of the Threlkeld microgranite was also recognized by O'Brien *et al.* (1985) who showed that, along with other Lake District granites, it follows a calc-alkaline trend on an AFM diagram. The Threlkeld microgranite has a small negative Eu anomaly indicating that plagioclase fractionation may have occurred before intrusion (O'Brien *et al.*, 1985). There are some significant similarities in trace element geochemistry between published BVG compositions (e.g. Fitton *et al.*, 1982) and the Threlkeld microgranite, but there are also some differences, particularly with respect to P, Nb, Zr and Y, suggesting that they either had different fractionating phases, or different sources (O'Brien *et al.*, 1985). Low initial $^{87}Sr/^{86}Sr$ ratios of 0.7055 (Wadge *et al.*, 1974) attest to the I-type nature of the Threlkeld microgranite.

Garnets in the Threlkeld microgranite show a wide range of compositions, in contrast to the restricted compositions of those in the host rock (Caunt, 1984). There is a compositional overlap between garnets from the Threlkeld microgranite and garnets from the BVG. The Threlkeld microgranite garnets may be magmatic in origin (Oliver, 1956a, 1956b) or they may be xenocrystic (Rastall, 1940; Fitton, 1972). Caunt (1984) suggested that incorporation of Skiddaw Group material enriched the microgranite magma in Al_2O_3 and Fe_2O_3 allowing moderately low-pressure crystallization of garnet (cf. Fitton *et al.*, 1982 for garnet crystallization in BVG rocks).

The age of the Lake District intrusions, including the Threlkeld microgranite, has been a major debate since the beginning of the 20th century (e.g. Marr, 1900; Harker, 1902; Rastall and Wilcockson, 1915). The relationship of the Threlkeld microgranite to the contact between the Skiddaw and Borrowdale Volcanic groups is of crucial importance in determining the timing of its intrusion. Green (1917) suggested that the Threlkeld microgranite is a sill intruded into a conformable contact between the Skiddaw and Borrowdale Volcanic groups. Taking into account cleavage in the microgranite he suggested an age that was post-lower BVG but pre-Devonian. Hadfield and Whiteside (1936) considered the microgranite to be a laccolith intruded below the BVG. They found xenoliths of BVG material in the microgranite and also proposed that the intrusion post-dates the lower BVG.

A different view was expressed by Rastall (1940). Based on his discovery of a xenolith of sharply folded Skiddaw Group material within the microgranite, Rastall (1940) argued that because folding of the Skiddaw Group was Caledonian, the microgranite must be Caledonian or younger. Wadge (1972) interpreted the contact between the Skiddaw Group and the BVG as an angular unconformity, suggested that the stock-like Threlkeld microgranite was intruded into the Skiddaw Group and that it was then partially eroded before deposition of the overlying BVG. Subsequently, the excavation at Bramcrag Quarry exposed field relationships that prove clearly that the Threlkeld microgranite is younger than the lowest strata of the BVG (Wadge *et al.*, 1974).

Gravity data presented by Bott (1974) show an anomaly overlying both the Skiddaw granite and the Threlkeld microgranite, but a more recent interpretation of the gravity data by Lee (1986) revealed that each intrusion has a separate Bouguer anomaly. An anomaly beneath the NE margin of the Threlkeld microgranite (Lee, 1986) was interpreted as a separate granite cupola corroborating Firman's (1978b) interpretation of the outcrops of the Threlkeld microgranite as a single irregular laccolith.

The Threlkeld microgranite is considered to be a subvolcanic intrusion related to the extrusive rocks of the BVG (Rundle, 1992), and it must therefore be Ordovician in age (older than *c.* 440 Ma). The Rb-Sr isochron age of 445 ± 15 Ma for the Threlkeld microgranite reported by Wadge *et al.* (1974) was recalculated by Rundle (1981) as 438 ± 6 Ma. Rundle (1992) acknowledged that this date could represent either the emplacement age of the microgranite or a subsequent 'resetting' event. He suggested that the emplacement of the Eskdale granite, which he had dated at about 430 Ma using Rb-Sr and K-Ar methods, may have been responsible for the resetting event. However, recent U-Pb analyses of zircons gave an age of 450 ± 3 Ma for the emplacement of the Eskdale granite and 452 ± 4 Ma for the Ennerdale granite (previously 420 ± 4 Ma using a Rb-Sr isochron; Rundle, 1992) suggesting that the Rb-Sr whole rock and K-Ar mineral methods do not correspond to the emplacement of the intrusions, but to a resetting event (Hughes *et al.*, 1996). This in turn casts doubt on the accuracy of the Rb-Sr isochron age as the date of emplacement for the Threlkeld microgranite. Hughes *et al.* (1996) suggested that there were only two phases of acid magmatism relating to the exposed parts of the Lake District batholith: the Eskdale, Ennerdale and Threlkeld intrusions belong to a subduction-related Caradoc phase whereas the Shap and Skiddaw intrusions belong to a later, Devonian phase.

The significance of the sheared contact between the Threlkeld microgranite and the lower BVG is uncertain. The presence of apophyses of microgranite within the overlying sedimentary rocks suggests that absolute movement along this contact was minimal (Campbell, 1995).

Conclusion

The age of the Threlkeld microgranite and its relationship with the Ordovician country rock and other Lake District intrusions has been the subject of debate for many years. The relationships exposed at Bramcrag Quarry are crucial in constraining the further interpretation of the isotopic dates. The Bramcrag Quarry site is the only locality that demonstrates that the Threlkeld microgranite intrudes both the Skiddaw Group and the lowest part of the Borrowdale Volcanic Group. The intrusion is considered, on petrographical and geochemical evidence, to be contemporaneous with the thick ignimbrites of the upper part of the Borrowdale Volcanic Group. The available Rb-Sr age of 438 ± 6 Ma post-dates the cessation of volcanism and may represent either the age of emplacement of the Threlkeld microgranite or a resetting event. Accurate U-Pb dates on zircons may offer a resolution to this problem.

BOWNESS KNOTT (NY 112 156)

D. J. Fettes

Introduction

Bowness Knott is bisected by the nearly NE-trending contact between the Ennerdale intrusion to the east and the Skiddaw Group rocks to the west (Figure 4.33). The GCR site provides excellent sections through this contact and allows an examination of the relationship of the intrusion to the regional deformational events.

The Ennerdale intrusion (previously referred to as the Ennerdale 'Granophyre') is one of the major igneous bodies of the Lake District and as such it is a surface expression of the Lake District batholith (Bott, 1974). The intrusion crops out between Buttermere in the north and Wasdale in the south, a distance of *c.* 14 km with an average width of *c.* 4 km. It consists predominantly of a relatively uniform pink or grey medium- to fine-grained granite. There are also a number of localized zones of more basic and related hybrid rocks, notably at Burtness Combe above Buttermere, Bowness Knott, the Bleng Valley and at Mecklin Wood in Wasdale.

The body was first mapped by the early surveyors of the Geological Survey (Ward, 1876). The first comprehensive account was given by Rastall (1906). Subsequent detailed accounts were given for those parts of the mass within the Gosforth (37) and Whitehaven (28) geological sheets by Trotter *et al.* (1937) and Eastwood *et al.* (1931) respectively. More recently, the mass and its regional setting were described by Clark (1963) who included petrochemical and petrogenetic discussion.

There has been a number of studies on the radiometric age of the intrusion (Brown *et al.*, 1964; Rundle, 1979; Hughes *et al.*, 1996) and on the geophysical characteristics (Bott, 1974; Lee, 1986; Evans *et al.*, 1994). Many of these studies have focused on the regional setting of the mass, and its age relative to the other igneous complexes and the regional tectonism of the Lake District.

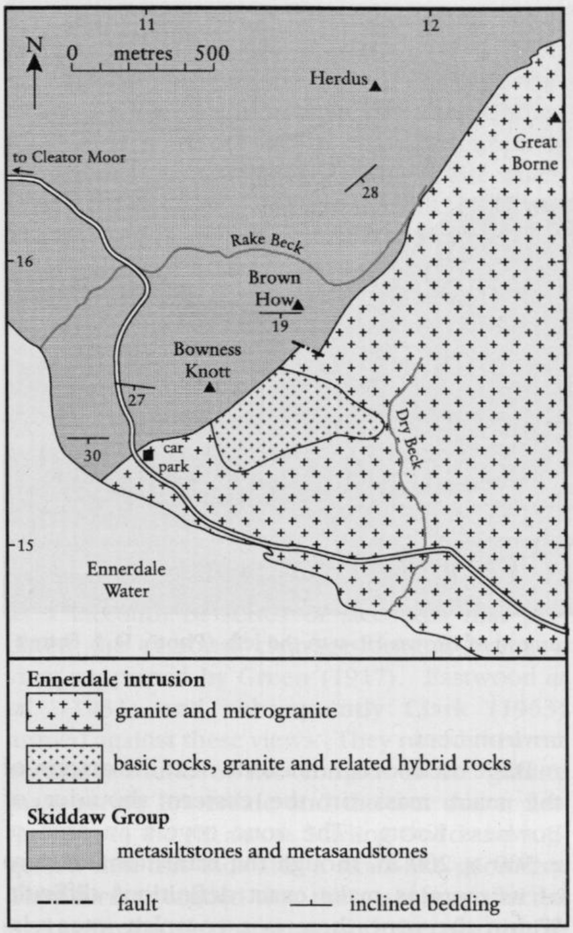

Figure 4.33 Map of the Bowness Knott GCR site.

Description

Bowness Knott (333 m) lies on the north side of Ennerdale Water guarding the entrance to the main valley (Figure 4.34). It has steep crag and scree-covered slopes to the west and south, falling off more gently to the east, where available exposure is masked by recent afforestation. To the north the ground flattens off with the minor top of Brown How before rising steeply to Herdus and Great Borne. Rake Beck, which rises between these last two hills, flows steeply down to Brown How where it turns through a right angle and continues down the north side of Bowness Knott.

The contact between the Ennerdale intrusion and the country rocks is steep or near vertical in this area. It runs up a gully near the eastern end of the crags on the south side of Bowness Knott, across the shoulder east of the top, east of Brown How and up the east side of Rake Beck. Over most of its length the contact can be localized to a few metres, though it is only exposed on the south slope of Great Borne. Its trend is parallel to one of the principal joint directions in the intrusion and the country rock.

The country rocks belong to the Buttermere Formation of the Skiddaw Group and are believed to be of late Arenig or early Llanvirn age (Cooper *et al.*, 1995). They are predominantly composed of finely laminated siltstone with subordinate sandstone and mudstone. The bedding strikes around E–W, with low dips to the south; to the north of the GCR site the strike swings nearer to NE–SW. The slump folds and soft-sediment deformational structures characteristic of this formation elsewhere are not significantly developed in this area though small slump folds are cut by a granite vein at one locality (1116 1539). Tectonic structures are also sparse and the regional cleavage is generally absent or only weakly developed; where present it strikes broadly parallel to bedding but with steeper dips. Within the GCR site the rocks are all thermally metamorphosed by the intrusion, developing a hard splintery texture. The hornfels has a greenish-grey colour but as the main contact is approached alteration on joints marked by pale-pink or red staining may pervade the whole rock giving it a pale bleached look. Hughes and Fettes (1994) recorded the presence of biotite and incipient spots of cordierite and/or andalusite close to the contact. Quartz veins are widely developed within these rocks, both as thin laminae parallel to the bedding and as larger cross-cutting structures. These veins are themselves cut by the granitic veins.

Marginal granitic veining within the Skiddaw Group is generally sparse though where present it may be relatively abundant, for example on the crags above the Bowness Knott car park (109 155). Most of the veins persist for only a few tens of metres away from the main contact. The veins are irregular and branching and range from a few centimetres to two or three metres in width. They may be markedly cross-cutting in respect of the sedimentary bedding and have sharp margins and no sign of chilling. Locally, (for example at 1118 1540), the marginal veins may become so numerous near the main contact that they isolate large blocks of the country rock. However, such effects are uncommon, as are true xenoliths.

The main mass of the Ennerdale intrusion is

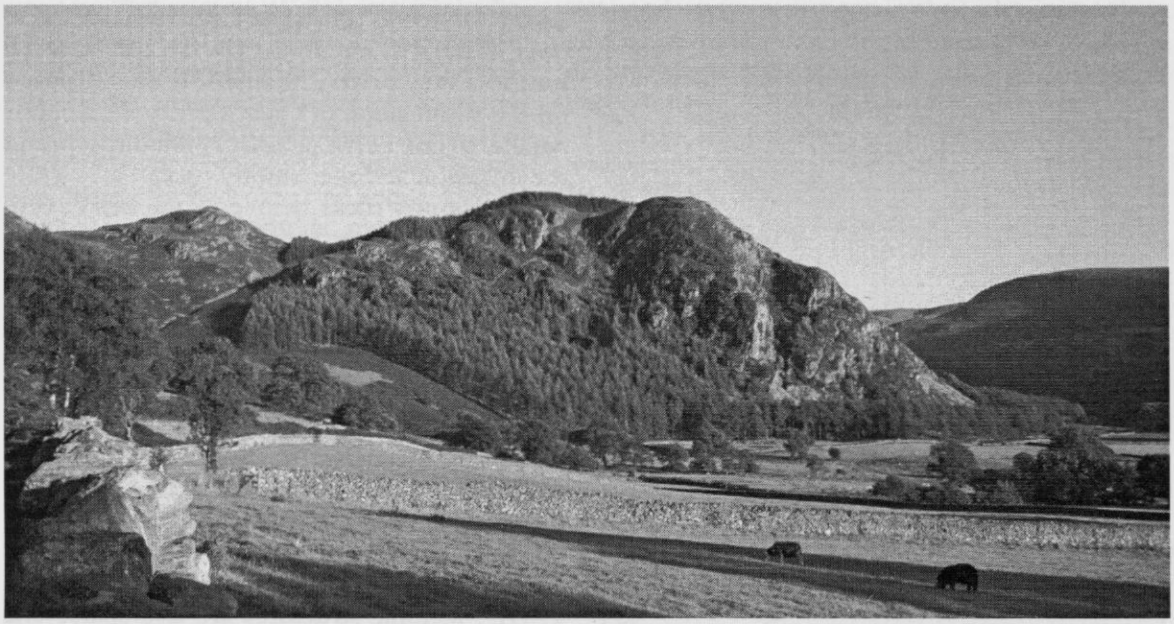

Figure 4.34 Bowness Knott from the west with the low summit of Brown How to the left. (Photo: D. J. Fettes.)

composed of a relatively uniform pinkish medium- to fine-grained granite, commonly with chloritic clots and white feldspar phenocrysts. Locally, particularly towards the margins, the granite may become more felsitic. Patches of light-coloured microgranite occur within the mass and locally these have transitional contacts with the main granite, though elsewhere they appear to be later; they probably relate to a series of late-stage minor acid intrusions within the mass including microgranites, fine-grained granophyric microgranites and aplitic microgranites (Eastwood *et al.*, 1931; Clark, 1963). The mass is well jointed with two or three near-vertical sets and one sub-horizontal set. The rock consists of quartz, plagioclase, potash feldspar, biotite and chlorite; accessories include epidote, iron oxides, titanite, apatite and zircon. Rastall (1906) showed that granophyric textures are generally absent from the margins of the body and increase towards the centre where, the '... intergrowth becomes continuously finer in texture, and of an increasingly perfect micropegmatitic structure'. Chemical analyses of the granite (Clark, 1963; O'Brien *et al.*, 1985; Millward *et al.*, in press) show the body to be chemically coherent but with anomalously high soda and correspondingly low potash values, suggesting some form of metasomatic exchange. The chemical characteristics are consistent with an I-type granite generated within a volcanic-arc environment.

Basic rocks occur in a zone near the margin of the main mass on the eastern shoulder of Bowness Knott. The zone covers an area of *c.* 500 × 200 m, though the transitional nature of its margins make exact definitions difficult. Within the zone there is a complex inter-relationship of rock types. Three main varieties may be recognized. The first and most basic variety is a dark compact doleritic rock that contains some interstitial potash feldspar (Clark, 1963); the second is a dark-grey dioritic rock which, in part, grades into the third variety comprising the common granite of the mass. On crags at 114 155 veins of granite cut the more basic varieties and blebs of granitic material lie within more basic varieties. The more basic varieties are most numerous near the main contact and to the east the amount of ferromagnesian minerals in the intermediate types falls eventually to give way to the uniform granite of the mass. Clark (1963) described dioritic rocks cut by a vein of granite that is itself cut by a vein of finer-grained granite. Rastall (1906) described a peculiar form of intermediate rock, which he termed 'needle rock', characterized by long acicular crystals of uralitized augite.

Minor intrusions are found throughout the GCR site. Clark (1963) described a series of microdiorite dykes on and around Bowness Knott. They vary from 0.2–4 m in width and have SE and SW trends. They are composed of plagioclase and secondary actinolitic amphibole, possibly after pyroxene. Acid dykes also occur, many having a splintery felsitic appearance (Eastwood *et al.*, 1931). A notable example is provided by a 3 m-thick spherulitic felsite which trends ENE and crosses Rake Beck (1136 1603). The spherulites, which are up to 15 mm across, are regular and arranged in bands parallel to the margins. Other examples of major acid veins may be examined at 110 156 where a 2 m vein cuts obliquely across the bedding lamination and at 1143 1602 where a 2 m vein trending at 135° runs along a major joint and is itself finely jointed at its margins.

Interpretation

Rastall (1906) regarded the Ennerdale intrusion as a laccolith or series of laccoliths that pre-dated the regional cleavage-forming event, a view supported by Green (1917). Eastwood *et al.* (1931) and subsequently Clark (1963) argued against these views. They noted the near vertical attitude of the contact of the granite mass across Ennerdale and the fact that it flattens out to the NE across Starling Dodd and suggested that this indicates a stock-like geometry. They further argued that the mass was affected by regional-scale thrusting and therefore must pre-date that event. They noted that the granophyre cuts folds in the metasedimentary rocks and tentatively suggested that the veins must post-date the cleavage, assuming that the latter is genetically related to the folds. However, if the folds are accepted as slump structures the basis of the argument fails. The early radiometric dates on the granite seemed to support the late Caledonian age; Brown *et al.* (1964) derived a whole-rock K-Ar age of 370 ± 20 Ma for the main granite, and Rundle (1979) a whole-rock Rb-Sr age of 420 ± 4 Ma. However, Hughes and Fettes (1994) concluded from thin-section studies and variations in the nature of the cleavage across the aureole that the cleavage has been imposed on the hornfels and that in consequence the intrusion pre-dates the regional deformation. This view was supported by Hughes *et al.* (1996) who presented a U-Pb zircon age of 452 ± 4 Ma, indicating a late Caradoc age of intrusion.

Lee (1989) interpreted the Ennerdale mass as a shallow laccolith *c.* 1–2 km thick overlying a denser granitic mass. Evans *et al.* (1994) refined this model and suggested that the mass consists of a 1100 m-thick laccolith underlain by further laccolith-style members of the Lake District batholith.

Much discussion has taken place on the basic and acid complexes (Rastall, 1906; Eastwood *et al.*, 1931; Clark, 1963). It is generally accepted, on the basis of the complex age relationships, the transitional rock types and the confinement of the basic rocks to the margins of the mass, that there has been some form of hybridization between an early basic magmatic phase and the later granitic magma, probably by some form of metasomatic exchange. Both Clark (1963) and Millward *et al.* (in press) argued that the early basic phase was dioritic and that the doleritic rocks represent some form of cumulate or early differentiate.

The Ennerdale intrusion is most probably a subvolcanic intrusion emplaced in a supra-subduction zone setting as a series of two or three magmatic pulses. Locally, the host rocks were metamorphosed and hardened, and this carapace largely resisted the subsequent regional cleavage-forming events.

Conclusions

The Bowness Knott GCR site provides excellent sections through the contact of the Ennerdale intrusion and the host Skiddaw Group rocks and allows a study of the nature of the intrusion and, in particular, its age relative to the regional events.

The Ennerdale intrusion, one of the surface expressions of the Lake District batholith, is a relatively uniform, pink granite, characterized for the greater part by granophyric intergrowths and feldspar phenocrysts. Diorite phases occur within the main mass and as minor intrusions around Bowness Knott; they have locally hybridized with the slightly later granite. The hybrid rocks contain a range of rock types including the famous 'needle rock' well seen on the eastern shoulder of Bowness Knott.

The regional cleavage is only incipiently developed in the aureole of the intrusion and overprints the aureole minerals indicating that its development post-dates the intrusion. Radiometric dating suggests a late Caradoc age for the intrusion linking it with the formation of the Borrowdale Volcanic Group. Chemical characteristics of the mass are consistent with a subvolcanic setting for its intrusion.

BECKFOOT QUARRY (NY 164 003)

B. Young

Introduction

Beckfoot Quarry is located in the central part of the Eskdale pluton, the westernmost exposed portion of the largely concealed Lake District batholith. The pluton consists of two major components: a well-exposed northern granite and a generally poorly exposed southern granodiorite. The geology and petrography of the Eskdale pluton has been described by Dwerryhouse (1909), Simpson (1934), Trotter *et al.* (1937), Firman (1978b), Ansari (1983), Young (1985), Young *et al.* (1988) and Millward *et al.* (in press). The geochemistry of the granites has been discussed by Ansari (1983) and O'Brien *et al.* (1985). Within the northern part of the pluton three main facies of granitic rocks may be distinguished: medium-grained aphyric muscovite granite (the so-called 'normal' granite of several authors); a series of microgranites that vary from aphyric to markedly porphyritic and megacrystic; and a local development of a coarse- to very coarse-grained granite. The distribution of these facies is shown on recent Geological Survey maps of the area (1:25 000 special sheet, 1991; 1:50 000 Sheet 38, 1996).

Previously held views that the Eskdale pluton is a late Caledonian intrusion, similar in age to the granites of Shap and Skiddaw, were dispelled by the Rb-Sr age of 429 ± 4 Ma (Rundle, 1979) and the discovery of cleavage within the Eskdale granite (Allen, 1987). More recently, Hughes *et al.* (1996) have published a U-Pb age of 452 ± 4 Ma, which confirms the late Ordovician age of this subvolcanic intrusion.

The Beckfoot Quarry GCR site (Figure 4.35) is the only site selected for the GCR within the granite of the Eskdale pluton; the contrasting granodiorite that comprises the southern portion of the Eskdale pluton is described in the Waberthwaite Quarry GCR site report (see below). Good examples of the 'normal' granite and its relationships with the microgranite facies are exposed (Figure 4.35). Beckfoot Quarry was chosen for sample collection for U-Pb dating on zircon because the granite there is xenolith free and largely unaffected by vein mineralization (Hughes *et al.*, 1996). Therefore, it is a key site in understanding the magmatic history of the Lake District.

Description

Beckfoot Quarry is an abandoned quarry within the medium-grained 'normal' granite and microgranite facies of the Eskdale pluton (Figure 4.35). Microgranites are common within the granite, especially in the NE part of the intrusion. The commonly complex field relationship of the microgranites with the 'normal' granite has been described by Young (1985).

Medium-grained 'normal' granite forms much of the eastern face of the quarry. This rock is typically a pale-pink equigranular granite composed of perthitic feldspar, sodic plagioclase and quartz with some muscovite and biotite. Accessory minerals are generally scarce but zircon is common in altered biotite. Tourmaline is found locally as clusters of radiating black crystals coating joint surfaces (Jones, 1915). Much of the central and western parts of the quarry expose a variety of microgranite lithologies. These are mineralogically identical to the granite, but commonly exhibit various textures even within a single small exposure. Aphyric and porphyritic variants occur, the latter with abundant quartz or feldspar phenocrysts, commonly in clustered aggregates. The relationship of the microgranite to the granite within the quarry is not clear, though in the immediate neighbourhood of the quarry the microgranites appear to lie beneath the granite.

Both the granite and microgranite are cut by a roughly WSW–ENE vein composed of microgranite fragments cemented by quartz and pale-fawn dolomite. Some haematite staining occurs locally on joint surfaces within the microgranite.

Interpretation

The identical mineralogical composition of the 'normal' granite and associated microgranites within the Eskdale pluton are consistent with a co-magmatic origin. Moreover, the complex and often intricate relationships between these facies have been cited as the result of partial mixing of two or more pulses of the same, or extremely similar, magma in a partially crystallized or plastic state (Young *et al.*, 1988). Clusters of quartz and feldspar phenocrysts within the microgranites have been interpreted as partially absorbed xenoliths of coarsely crystallized granite

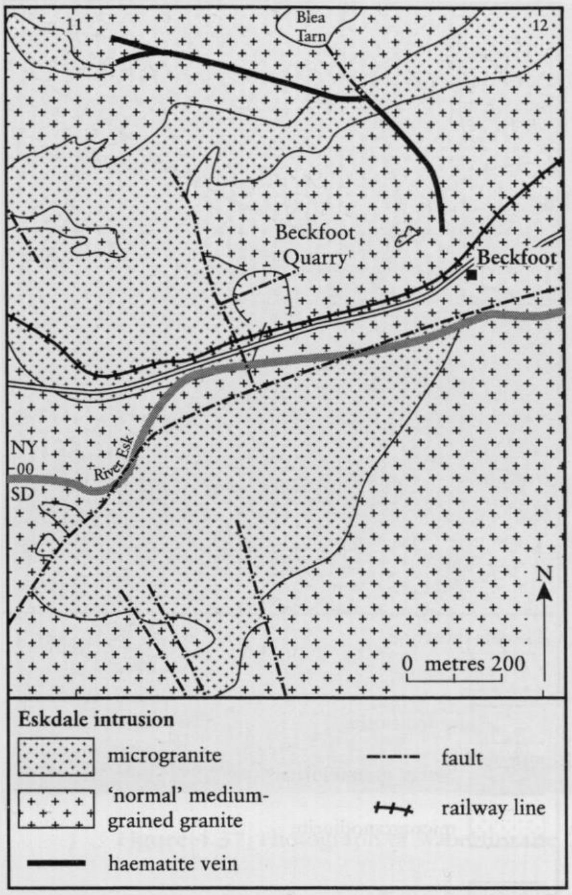

Figure 4.35 Map of the area around Beckfoot Quarry.

(Millward *et al.*, in press).

Mapping suggests that the Eskdale granite exposed in the central and upper parts of Eskdale lies within a few hundred metres of the roof of the intrusion. Outcrops of hornfelsed Borrowdale Volcanic Group rocks overlie granite NE of Blea Tarn (168 012) and NE of Boot (181 014; 185 016).

Ansari (1983) and O'Brien *et al.* (1985) noted the differences in geochemistry between the granite and granodiorite in the Eskdale pluton. Analytical data for the lithologies emphasize the more evolved nature of the former and show a compositional hiatus between them. Ansari (1983) concluded on this basis that there is no genetic relationship between the granite and granodiorite, and that they are effectively separate intrusions. However, O'Brien *et al.* (1985) suggested that the granodiorite and granite are petrogenetically linked by crystal–liquid fractionation of a common parental magma intermediate in composition to the granite and granodiorite. This is supported by similar initial $^{87}Sr/^{86}Sr$ ratios of 0.7076 ± 0.0005 and 0.7073 ± 0.0007 for the granite and granodiorite, respectively (Rundle, 1979).

Compositional differences are present between the three principal granite lithologies (Millward *et al.*, in press). Early, coarse-grained, predominantly primary textured granites show consistently lower levels of differentiation compared with 'normal' granite. By contrast, the microgranites, which record a spectrum of two-phase crystallization textures, span or exceed the compositional range of the coarse and normal granites. Crystallization of early magma, represented by the coarse granite, produced residual, more evolved melts that locally infiltrated, invaded and disrupted to varying degrees zones of partly crystallized granite, producing the more chemically variable mixed or hybridized compositions.

An end-Silurian or Devonian age for the granite was inferred for many years and only Green (1917) favoured an Ordovician age. The first radiometric date on the Eskdale granite was a Rb-Sr isochron age of 429 ± 4 Ma (Rundle, 1979), thus clearly establishing an Early Palaeozoic age and a link with the magmatic episode typified by the subduction-related volcanism of the Borrodale Volcanic Group. Allen (1987) noted the presence of cleavage locally within parts of the Eskdale granite though this cleavage is not seen in Beckfoot Quarry. The U-Pb age of 452 ± 4 Ma published by Hughes *et al.* (1996) from zircons obtained from the 'normal' granite of Beckfoot Quarry confirms the Eskdale pluton as late Ordovician and probably subvolcanic.

Conclusions

The Beckfoot Quarry GCR site contains good examples typical of both the medium-grained ('normal') and microgranite facies of the Eskdale pluton. The Eskdale granite is the western part of the largely concealed Lake District batholith and has been shown to be a late Ordovician subvolcanic intrusion. The quarry provided the sample from which the late Ordovician U-Pb zircon age of 452 ± 4 Ma was obtained.

WABERTHWAITE QUARRY (SD 112 944)

B. Young

Introduction

Waberthwaite Quarry, located between Broad Oak and Waberthwaite in west Cumbria, provides one of the very few exposures of the biotite granodiorite facies within the generally poorly exposed southern granodiorite of the Eskdale pluton (Figure 4.36). The northern well-exposed granite has been described in the Beckfoot Quarry GCR site. Important descriptions of these rocks include those by Dwerryhouse (1909), Simpson (1934), Trotter *et al.* (1937), Firman (1978b), Ansari (1983), Young (1985), Young *et al.* (1988) and Millward *et al.* (in press). The biotite granodiorite facies is shown separately from the granodiorite on the Geological Survey 1:50 000 Sheet 38 (1996), though this distinction is not made on the 1:25 000 special sheet (1991). The presence within the granodiorite at Waberthwaite of almandine-rich garnet in the granodiorite and associated aplitic microgranites, and within some of the xenoliths is noteworthy.

Description

Though very poorly exposed the Eskdale granodiorite includes a number of lithologies (Figure 4.36). Microgranodiorite is commonly developed adjacent to the margin of the intrusion. The main mass of the body appears to be composed of a pink medium-grained granodiorite in which some biotite and amphibole are generally present. Both of these rock types are commonly altered with extensive sericitization and saussuritization of feldspar, and chloritization of mafic constituents. In the vicinity of Waberthwaite Quarry a distinctive grey, biotite-rich granodiorite occurs, though the relationship of this to the main body of granodiorite is not clear. This rock is best seen in Waberthwaite Quarry. Alteration is less intense in this rock than in much of the granodiorite body.

Though Waberthwaite Quarry has effectively been disused for many years (Figure 4.37), small quantities of rock have been extracted in recent years for use as dimension stone. These have been marketed as 'Broad Oak Granite'. Despite these small-scale workings, the quarry faces at

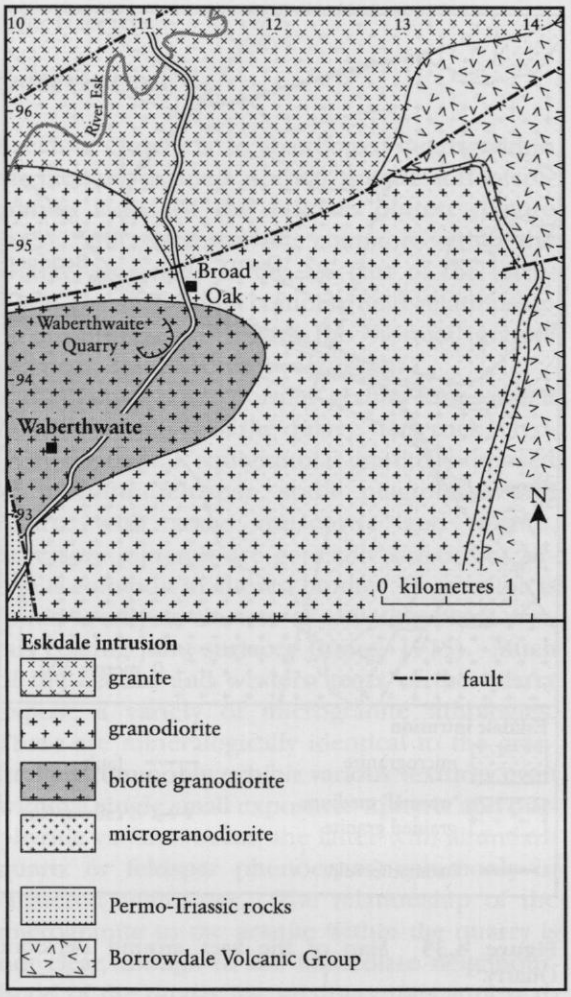

Figure 4.36 Map of the Eskdale granodiorite around Waberthwaite Quarry.

the time of writing are rather weathered and the site is considerably overgrown. The granodiorite exposed in the quarry is a grey medium-grained biotite-rich facies. Mafic xenoliths are common and a few narrow (up to 15 cm) aplitic veins are present.

Typically the biotite-rich granodiorite consists of plagioclase, orthoclase, some perthite and quartz with abundant, commonly fresh, biotite. Almandine garnet is locally conspicuous, both in the main mass of the granodiorite and in some biotite-rich xenoliths and aplitic veins. Ansari (1983) described its presence in equant crystals 1–2 mm in diameter intergrown with quartz and feldspar. Firman (1978b) noted that the garnets range up to 5 mm in diameter and that they commonly appear to be broken fragments of

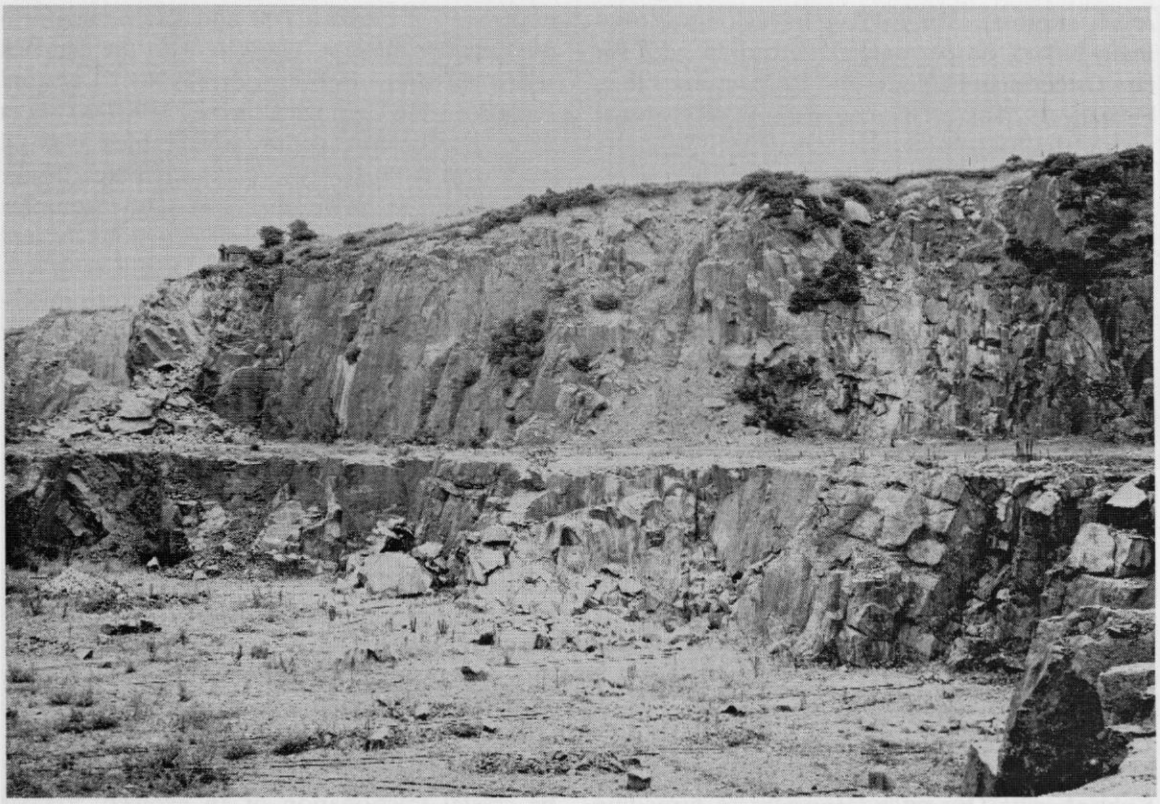

Figure 4.37 Photograph of Waberthwaite Quarry taken in 1935. (Photo: BGS no. A6707.)

euhedral crystals. A little amphibole is also present and tourmaline occurs both in the granodiorite and as clusters in aplitic veins. Accessory minerals include apatite, zircon and opaque oxides. Saussuritic alteration of plagioclase is common and perthite is extensively sericitized. Biotite is in places chloritized with the development of some secondary titanite and anatase.

The aplitic rocks are typically fine grained, equigranular and contain chloritized biotite together with more perthite than plagioclase. Almandine garnet and tourmaline are locally present.

Interpretation

The relative abundance of almandine garnet within the biotite-rich granodiorite has long been known. Simpson (1934) suggested that the garnet may be the result of a late-stage concentration effect in the crystallization of the granodiorite. Trotter *et al.* (1937) favoured assimilation of Borrowdale Volcanic Group rocks in the formation of the granodiorite, though they discounted the possibility of the garnets being derived from a garnetiferous lava. Firman (1978b) noted that many of the garnets appear to be broken fragments of euhedral crystals and their xenocrystic origin was advocated by Ansari (1983).

In his description of the Eskdale pluton Simpson (1934) referred to the presence of abundant xenoliths in the rock exposed in the higher parts of Waberthwaite Quarry, apparently overlying 'grey granite'. He interpreted the abundance there of xenoliths as evidence for the nearness of the roof of the intrusion. The exposures available today do not support Simpson's suggestion of an upper xenolith-rich zone. However, evidence from recent mapping of the Eskdale pluton by the British Geological Survey (Millward *et al.*, in press) is consistent with much of the exposed part of this body lying close to the original roof zone of the intrusion.

A geochemical comparison of the granite and granodiorite parts of the Eskdale pluton has been summarized in the Beckfoot Quarry GCR site (Ansari, 1983; O'Brien *et al.*, 1985; Millward *et al.*, in press). The Eskdale intrusion was originally linked, on petrogenetic grounds, with the late Caledonian Skiddaw and Shap granites (e.g. Firman, 1978b). The recognition of cleavage within the Eskdale granite (Allen, 1987) together with a Rb-Sr age of 429 ± 4 Ma (Rundle, 1979) suggested an early, pre-deformation date of emplacement. Though less precise, the isochron age of 429 ± 22 Ma obtained by Rundle (1979) for the granodiorite indicates that this part of the pluton may be of closely similar age. Field evidence of the age relationships is unclear though Young (1985) suggested that the granodiorite may be the earlier intrusion. The U-Pb zircon age of 452 ± 4 Ma for the Eskdale granite (Hughes *et al.*, 1996) has been discussed in the Beckfoot Quarry GCR site report, but an accurate age for the granodiorite is not available. However, if the very limited evidence of field relationships suggested by Young (1985) is accepted, the granodiorite must pre-date this slightly.

Conclusions

Waberthwaite Quarry is important in providing the best available exposures of the garnet-bearing biotite granodiorite facies of the Eskdale pluton. The quarry offers a unique opportunity to study mafic xenoliths in the intrusion, possibly derived from Borrowdale Volcanic Group. The comparative abundance of almandine garnet, at least some of which may be derived from country rocks, is noteworthy.

CARROCK FELL (NY 340 320–360 342)

D. Millward

Introduction

The Carrock Fell GCR site lies at the eastern extent of the Carrock Fell Complex, the largest mafic intrusion in the Lake District (Figure 4.38). The two principal sheet-like units of the complex, the Mosedale and Carrock divisions, are petrographically and geochemically distinct. The former is equivalent to the Carrock Fell Gabbro of Harker (1894, 1895b) and Eastwood *et al.* (1968), the Carrock Fell Gabbro Series of Harris and Dagger (1987) and the Mosedale series of Hunter and Bowden (1990). The 'diabase' of earlier workers, along with the 'granophyres' of Carrock Fell and Rae Crags form the Carrock division, equivalent to the Carrock series of Hunter and Bowden (1990). 'Division' is used on the Geological Survey 1:50 000 Sheet 23 (1997) for units within the complex to avoid confusion with the chronostratigraphical usage of 'series'. At its western extent the complex also contains three later felsic intrusions located along the Roughton Gill and Drygill fault systems: the Iron Crag and Red Covercloth microgranites and the Harestones rhyolite (Figure 4.38).

Mafic rocks within the complex show many of the features typical of small- to medium-size layered gabbroic intrusions. This type of igneous body is atypical among the Caledonian intrusions of England and Wales. The GCR site is the best-exposed section through the complex and includes good examples of those features that have been the subject of much research interest for more than a century. Geochemical data show that the Mosedale division is probably cogenetic with the continental-margin tholeiitic rocks of the Eycott Volcanic Group (Fitton, 1971; Hunter, 1980), and that the Carrock division was formed by crystal fractionation of an evolved, low-Mg tholeiitic basaltic magma (Hunter, 1980). The co-existence of the latter magma type with continental-margin volcanic suites makes this site of major importance in understanding the evolution of the Lake District magmatic province.

The complex was described first by Ward (1876), but Harker's (1894, 1895b) seminal works were a landmark in geology because, for the first time, physical principals were applied to field observations and the interpretations of in-situ differentiation processes within igneous intrusions. Later accounts of the complex include those by Eastwood *et al.* (1968), Skillen (1973), and Harris and Dagger (1987). However, the most important recent work is by Hunter (1980) whose study of the detailed petrology, mineralogy and geochemistry of these rocks resulted in a modern understanding of the crystallization and emplacement mechanisms. The account by Hollingworth (1937) of a field visit to Carrock Fell is a reminder of the popularity of the GCR site for excursions and there is an excellent field guide (Hunter and Bowden, 1990).

Description

The east-facing crags of the eastern part of

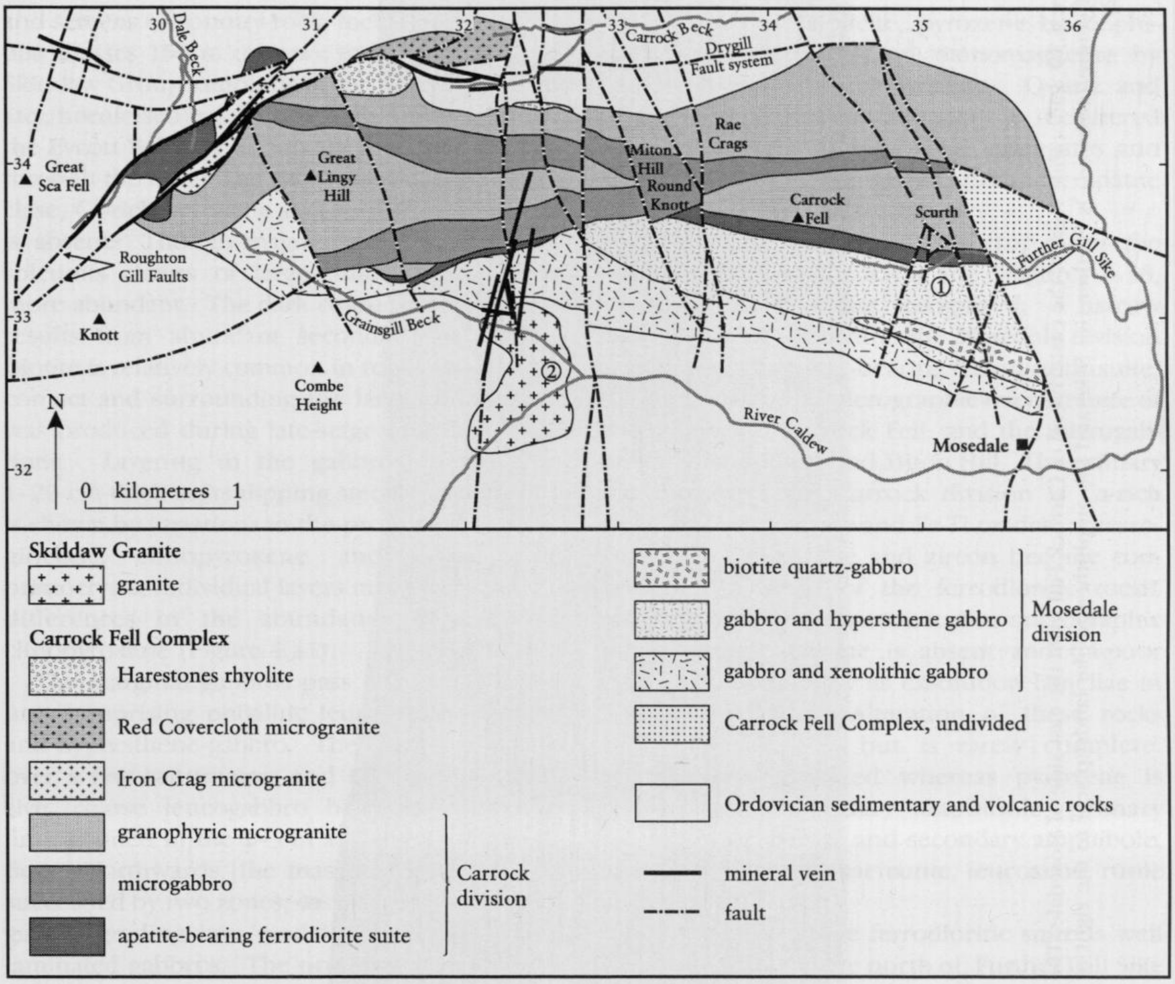

Figure 4.38 Map of the Carrock Fell Complex and the Skiddaw granite (after BGS 1:50 000 Sheet 23, 1997).

Carrock Fell rise from the Caldew river valley at about 220 m above OD to the summit of Carrock Fell at 660 m (Figure 4.39). The NNW-trending line of crags is formed by the Carrock End Fault, which juxtaposes the Carrock Fell Complex on the west against Skiddaw Group mudstones to the east (Figure 4.40); the latter are deeply eroded and extensively drift covered. Skiddaw Group rocks are exposed in the south of the GCR site.

The Mosedale division crops out in the southern part of the complex and consists dominantly of layered ortho- and mesocumulate gabbros. A broad symmetry of melagabbro at the margins passing progressively inwards into gabbro and leucogabbro, with a central mesocratic gabbro, has been recognized since Harker's classic work. Three sheet-like units are defined (Figure 4.40) amalgamating some of the divisions of Eastwood *et al.* (1968). The first unit crops out along the contact with the Skiddaw Group, and comprises gabbro and hornfelsed contact gabbro. This is succeeded to the north by poikilitic leucogabbro, gabbro and hypersthene-gabbro. Intruding the second unit in the east of the division is a westerly thinning wedge of biotite quartz-gabbro. Modal layering, mineral lamination and cryptic variation are characteristic features of the Mosedale division.

On the southern flanks of Carrock Fell, relatively homogeneous, medium-grained gabbro is in contact with folded mudrocks of the Skiddaw Group. The irregular sharp contact dips very steeply to the south. The mudrocks are hornfelsed and some pelitic beds contain garnet. The locally chilled gabbro contains many xenoliths

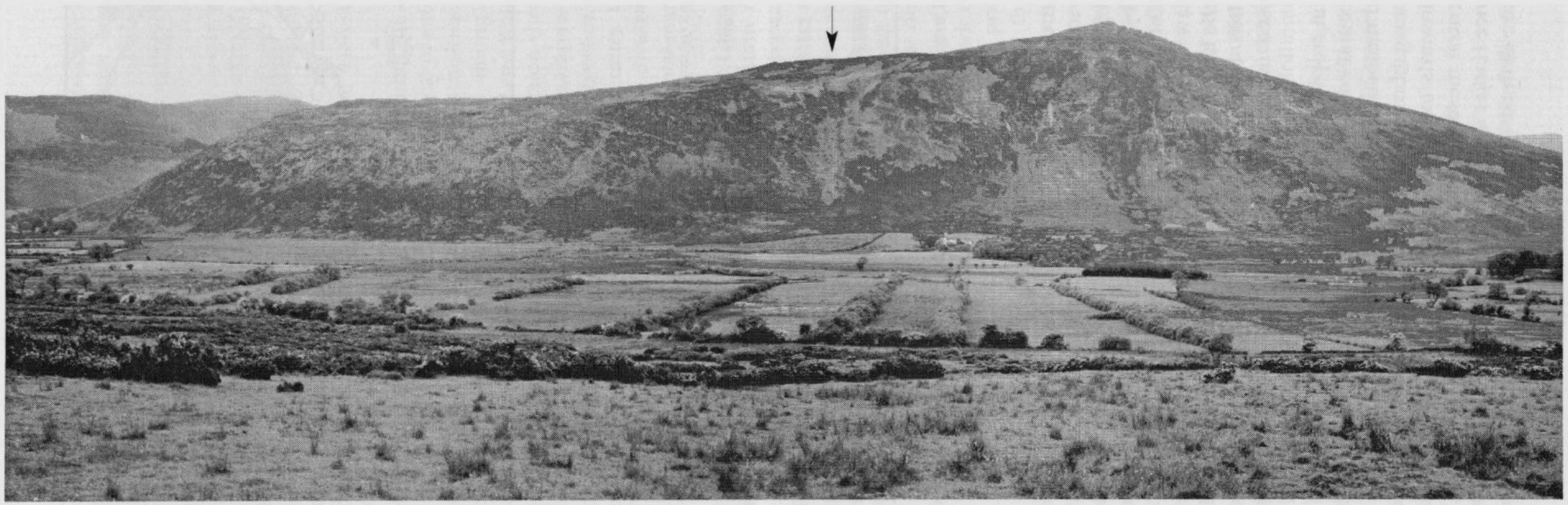

Figure 4.39 Panoramic view of the eastern end of Carrock Fell from the east side of Mosedale. The Caldew valley and the village of Mosedale are located far left. The stream just left of centre (arrowed) is Further Gill Syke and the amphitheatre-like landslip scar to the right of this, beneath the summit, is the Scurth. (Photomosaic: BGS nos. A6751 and A6752)

and screens of country rock, including large tabular masses 150 m or more in length. Though Skiddaw Group xenoliths occur near to the contact, hornfelsed basalt and basaltic andesite from the Eycott Volcanic Group are more widespread through the unit. The gabbros comprise plagioclase, Ca-rich pyroxene and Fe-Ti oxides; olivine is absent. Though magnetite is present, conspicuous chains of large ilmenite grains are more abundant. The dark colour of these rocks results from abundant secondary amphibole. Biotite is relatively common in rocks close to the contact and surrounding the large xenoliths; it was produced during late-stage magmatic reactions. Layering in the gabbros, typically in 1–20 cm-thick units dipping steeply to the NNE, is shown by variations in the proportions of plagioclase, clinopyroxene and Fe-Ti oxide primocrysts; individual layers may be divided by differences in the abundance of poikilitic clinopyroxene (Figure 4.41).

The marginal gabbros pass northward into a unit comprising poikilitic leucogabbro, gabbro and hypersthene-gabbro. The contact is diffuse over a few centimetres and the normally massive, coarse leucogabbro becomes noticeably finer grained in the 2–3 m adjacent to the junction. Northwards, the massive leucogabbro is succeeded by two zones, each comprising leucogabbro grading into modally layered and then laminated gabbros. The northern zone is more mafic than the other and corresponds to the 'fluxion gabbro' of Eastwood *et al.* (1968). In these rocks concentrations of augite, hypersthene, plagioclase and oxides mark igneous lamination, which generally dips steeply north. Adjacent to the contact with the Carrock division are layered and laminated gabbros, particularly rich in ilmenite and titanomagnetite. These rocks have a more melanocratic, and locally mottled, appearance caused by hydrothermal alteration during emplacement of the Carrock division.

The mesocratic biotite quartz-gabbro is finer grained than the leucogabbros which it intrudes. The gabbro contains abundant quartz, along with augite, hypersthene and inverted pigeonite, and is the most evolved member of the Mosedale division. Though poorly exposed, the southern contact is gradational over 2–3 m, and at the northern margin biotite quartz-gabbro passes into coarser poikilitic leucogabbro.

Mosedale division rocks are variably affected by hydrothermal alteration with the replacement of plagioclase by sericite, pyroxene by amphibole and/or chlorite, and titanomagnetite by titanite, haematite or leucoxene. Quartz and alkali feldspar are more abundant in the altered rocks and there are interstitial aggregates and cross-cutting veins of calcite, prehnite, apatite and epidote.

Rocks of the Carrock division crop out in the northern part of the GCR site (Figures 4.38, 4.40). Three units are recognized: a narrow marginal zone adjacent to the Mosedale division comprising an apatite-bearing ferrodioritic suite; the main masses of micrographic microgranite of Rae Crags and Carrock Fell; and the microgabbro of Round Knott and Miton Hill. The primary mineralogy of the Carrock division is Ca-rich pyroxene, plagioclase and Fe-Ti oxides; accessory apatite, amphibole and zircon become conspicuous in some of the ferrodioritic rocks. Alkali feldspar and quartz occur as micrographic intergrowths. Olivine is absent and Ca-poor pyroxene occurs only as exsolution lamellae in Ca-rich pyroxene. Alteration of these rocks varies considerably but is rarely complete. Feldspar is sericitized whereas pyroxene is replaced by secondary amphibole, primary amphibole by biotite and secondary amphibole, and Fe-Ti oxides by haematite, leucoxene, rutile and titanite.

The orthocumulate ferrodioritic suite is well exposed in, and to the north of, Further Gill Sike (351 333) (Figure 4.40). There is complete gradation in the suite from ferrogabbro through ferrodiorite, ferromonzodiorite to ferromicrogranite; pegmatites also occur. The ferrodiorite is laminated in places. Ferrogabbro contains abundant Fe-Ti oxides and conspicuous acicular apatite up to 10 mm. The latter enables ready field distinction from oxide-rich gabbroic cumulates of the Mosedale division nearby. Locally, the ferrogabbros coarsen and pass into granophyric pegmatite. Intrusion relationships are highly variable from gradational transitions to sharp contacts; chilling is not present within the marginal zone.

The contact between the marginal ferrodioritic rocks and the Mosedale division is not seen. Crescumulate pyroxene and plagioclase is developed locally normal to the mapped margin of the Carrock division. To the north of the upper reaches of Further Gill Sike, porphyritic ferromicrogranite is chilled against the main mass of microgranite. A 5 m-wide zone of hornfelsed microgranite occurs within the ferromicrogran-

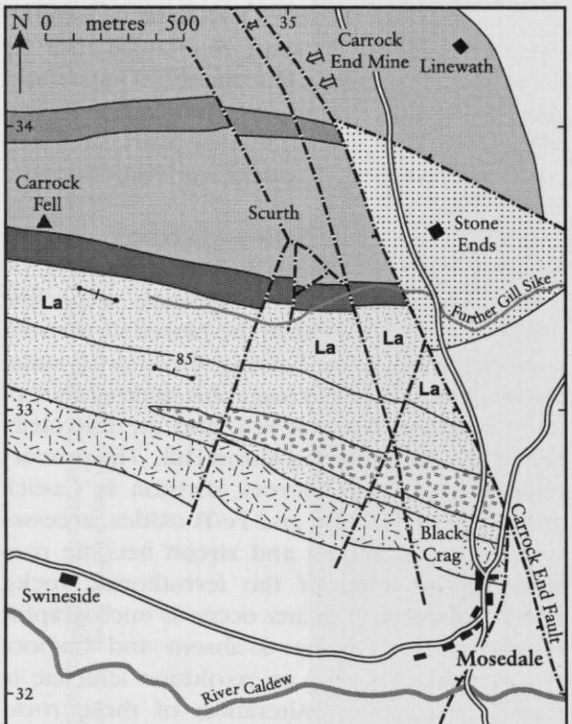

Figure 4.40 Map of the Carrock Fell GCR site.

ite and is possibly a stoped block from the main mass.

In the topographically highest parts of the intrusion, WNW of Further Gill Sike (349 334) there are drusy, granophyric pegmatitic rocks, in places containing dendritic and platy ferroaugite in spectacular growths up to 30 cm across. Locally, there are numerous easterly trending dykes of ferroandesite and dacite which may represent chilled cogenetic magmas.

The microgabbro (previously the 'diabase') is best seen on Round Knott (334 336), west of Carrock Fell summit (Figure 4.38). The layered augite-plagioclase cumulates there are altered. Fine-grained aplitic back-veining into the rocks south of Round Knott suggests that the microgabbro was intruded into the microgranite, and locally remelted it (Hunter and Bowden, 1990).

The main masses of reddish brown to reddish and pale pinkish-grey micrographic microgranite are best exposed in the Crags of the Scurth (348 337). Typically, zoned euhedral albite–oligoclase crystals are engulfed in micrographic intergrowths of quartz and feldspar; spherulitic intergrowths and some patches with microcrystalline felsitic texture are also present.

Interpretation

Ward (1876) considered the Carrock Fell Complex to be metamorphosed volcanic rocks. However, Harker (1894) proposed a primary igneous origin, explaining the decrease in the colour index of the gabbros within the Mosedale division as the result of the concentration, during crystallization, of more mafic magma towards the cooler margins of the intrusion. Eastwood *et al.* (1968) discussed some of the reasons why this mechanism was not favoured by petrologists and proposed that successive injections of crystal mush were derived from a deeper, unconsolidated intrusion. They also regarded the microgranite as the product of partial fusion of sialic crust caused by heat from the intrusion of mafic magma.

Later, the Mosedale division was interpreted by Hunter (1980) and Hunter and Bowden (1990) as a multiple-layered gabbroic intrusion, with replenishment events giving rise to later leucogabbro–gabbro–hypersthene-gabbro and biotite quartz-gabbro. A significant proportion of the Mosedale division may have been lost through faulting before emplacement of the Carrock division (Hunter and Bowden, 1990). Fitton (1971) and Hunter (1980) demonstrated the geochemical similarities and the probable cogenetic relationships between the Mosedale division and the Eycott Volcanic Group.

Emplacement of the Carrock division has

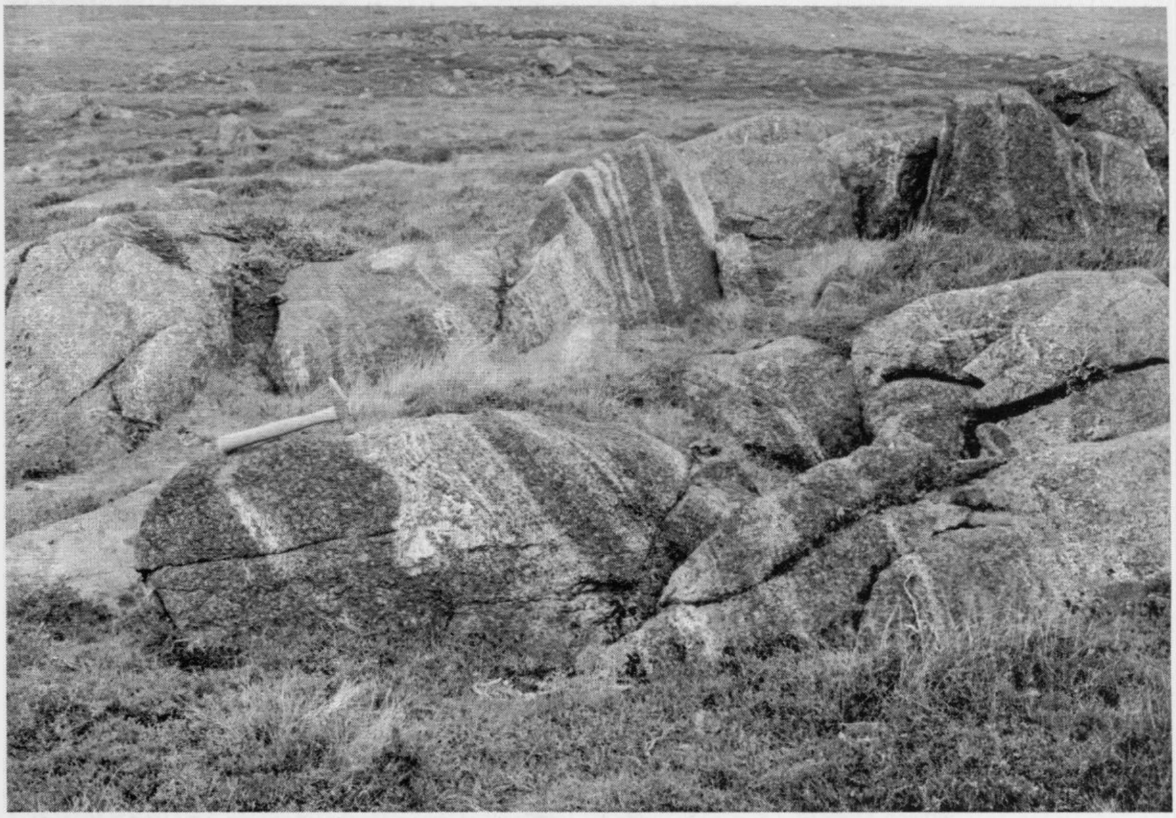

Figure 4.41 Modally layered gabbros from the Mosedale division. Alternation of leucocratic feldspathic and melanocratic mafic layers. (Photo: BGS no. A6743.)

been discussed also by Hunter (1980) and Hunter and Bowden (1990) who concluded that a low-Mg, basaltic magma fractionated along a tholeiitic liquid line of descent. The main masses of microgranite crystallized as a single entity and subsided from the uppermost and most evolved part of a zoned magma body. The ferrodioritic marginal rocks, considered previously to be hybrids (Harker, 1894, 1895b; Eastwood *et al.*, 1968), were clearly demonstrated to have crystallized along the side-walls, possibly from boundary layer flows that were feeding the evolved roof zone. Crystal fractionation was enhanced by rapid crystallization and subsequent filter pressing of interstitial liquid. Direct evidence for the proximity of the roof of the complex is not present within the GCR site, though to the west on Balliway Rigg (299 338), there is a sub-horizontal contact where ferrogabbro is overlain by andesite of the Eycott Volcanic Group (Figure 4.38). However, within the GCR site pegmatitic rocks of the Further Gill Sike area crystallized from water-saturated melt trapped beneath the roof of the intrusion (Hunter and Bowden, 1990).

The present dyke-like shape of the complex led Harker (1894) to propose that these rocks were emplaced nearly vertically. This has remained largely unchallenged, particularly for the Carrock division. Palaeomagnetic data have been used in support of near-vertical emplacement, though the Mosedale and Carrock divisions were not treated separately (Briden *et al.*, 1973; Faller and Briden, 1978). However, Harris and Dagger (1987) contended that emplacement of the Mosedale division as a sub-horizontal sheet-like body was consistent with the field and petrographical data and this is also entirely consistent with a genetic association with the Eycott Volcanic Group. A palaeomagnetic study (Piper, 1997) strongly supports emplacement of the Mosedale division sub-horizontally, followed by deformation and subsequent vertical intrusion of the Carrock division.

A wide range of ages for the complex has been proposed. Harker (1895b) concluded that the Carrock Fell Complex post-dates deformation of the Skiddaw and Eycott Volcanic groups and, from the petrographical similarities with some of the intrusions of the Hebrides, suggested a Palaeogene age (Harker, 1902). An Ordovician emplacement age for the complex was first argued by Green (1917). However, Eastwood *et al.* (1968) favoured a post-Caledonian, pre-Carboniferous age. The K-Ar whole-rock age of 356 ± 20 Ma of biotite hornfels from the contact aureole of the complex determined by Brown *et al.* (1964) is younger than 399 ± 6 Ma obtained for the Skiddaw granite by Miller (1961) and does not accord with field and petrographical evidence that the gabbros are earlier than the hydrothermal alteration and mineralization associated with the Skiddaw granite (Eastwood *et al.*, 1968). The anomalous radiometric date was probably caused by argon loss (Brown *et al.*, 1964).

An Ordovician age for the Mosedale division seems probable. The cogenetic relationship of these rocks with the Eycott Volcanic Group implies a similar age; the volcanic rocks have a late Llanvirn to Caradoc biostratigraphical age range (Downie and Soper, 1972; Millward and Molyneux, 1992). A minimum emplacement K-Ar age of 468 ± 10 Ma on biotite from the Mosedale division gabbro (Rundle, 1979) is late Llanvirn on the time-scale of Harland *et al.* (1990).

The Carrock division microgranite from Rae Crags post-dates the Caradoc (Longvillian) Drygill Shale Formation (Figure 4.38). It has a Rb-Sr isochron age of 416 ± 20 Ma (Rundle, 1979). Though it had long been accepted from field evidence that rocks of the Carrock division are younger than those of the Mosedale division (Harker, 1894; Eastwood *et al.*, 1968; Skillen, 1973), the differing radiometric ages obtained by Rundle were the first indication that there may have been a considerable time gap between emplacement of the two divisions. A radiometric age similar to the Carrock microgranite was also determined for the Harestones rhyolite (Rundle, 1979), but with the uncertainty in the significance of the many dates of about 420 Ma in the Lake District (see discussion in the Stockdale Beck, Longsleddale GCR site report), 416 Ma may be a resetting event.

The Carrock Fell Complex has been cited as evidence in the lengthy debate about the possibility of a late Ordovician orogeny in the Lake District. This idea was proposed originally by Green (1920) to explain the truncation of major fold-like structures such as the Ulpha Syncline by the Windermere Supergroup. The near-vertical emplacement of the Carrock Fell Complex and in particular the Carrock division, into steeply dipping rocks has been used as support for such an orogenic episode (Briden and Morris, 1973; Briden *et al.*, 1973; Faller and Briden, 1978; Piper, 1997; Piper *et al.*, 1997). However, the re-interpretation recently of the Ulpha Syncline and other related folds in the Borrowdale Volcanic Group as volcanotectonic structures (Branney and Soper, 1988) removes the need for an episode of large-scale folding in the late Ordovician. Tilting of the Skiddaw and Eycott Volcanic groups before intrusion of the Carrock division need not have resulted from an orogenic event as concluded by Piper *et al.* (1997), but from synvolcanic extensional faulting.

Conclusions

The Carrock Fell Complex is a multiple dyke-like mafic–felsic intrusion containing layered gabbroic rocks that was emplaced at the junction between the Skiddaw and Eycott Volcanic groups. It is unique in the Lake District and is atypical among the intrusive rocks of England and Wales. Components within the complex are mineralogically and geochemically distinct. The gabbros of the earliest, Mosedale division are considered to be associated with the continental-margin tholeiitic rocks of the Eycott Volcanic Group and are thus of Ordovician age. These are cut by the dyke-like Carrock division, comprising a gabbroic–ferrodioritic–micrograniticsuite related by fractional crystallization of a tholeiitic basalt magma and dated at 416 ± 20 Ma. The GCR site best illustrates the main features of, and the relationships between, these divisions. To the west of the site the complex also contains intrusions of feldspar-phyric micrographic microgranite and feldspar-quartz-phyric rhyolite that post-date, and are probably unrelated geochemically to, the Carrock division. The GCR site is an important focus of research into crystallization mechanisms in layered igneous rocks and is internationally significant. Though the rocks are petrographically, mineralogically and geochemically well characterized, the age of intrusion of the components remains to be understood fully.

HAWESWATER (NY 480 140–500 167)

D. Millward and B. Beddoe-Stephens

Introduction

The group of cleaved and presumably related, mainly mafic, intrusive rocks that crop out within an area of about 19 km^2 around the northern part of the Haweswater Reservoir collectively form the Haweswater 'Complex' of Nutt (1966, 1970, 1979). This is the largest group of mafic intrusions within the outcrop of the Borrowdale Volcanic Group (BVG) and the GCR site includes excellent examples of the principal rock types, including layered dolerite and gabbro (Figure 4.42). Marginal intrusive breccias are a significant feature. The presence of dolerite in the Haweswater area was reported by Dakyns *et al.* (1897) and Walker (1904), and the rocks were described by Green (1915b), Hancox (1934) and Nutt (1979). Nutt (1979) interpreted the intrusions as a subvolcanic magma chamber and the focus of an eruptive centre for the BVG.

Description

Geological maps and descriptions of the Haweswater intrusions by Hancox (1934) and Nutt (1970, 1979) show a group of dolerite and related rocks cropping out around the Haweswater Reservoir, encompassing part of Bampton Common and Naddle Forest from Willdale Beck in the north to Whelter Knotts (472 134) in the SW and Harper Hills in the SE. The intrusions comprise a combined outcrop area of about 2.6 km^2 within a total area of 19 km^2. The host rocks are lava and pyroclastic formations within the 3200 m-thick succession of the BVG in the eastern Lake District (Nutt, 1979). The major fault along Haweswater, interpreted by Nutt (1970) as separating intrusions within the lower part of the BVG succession to

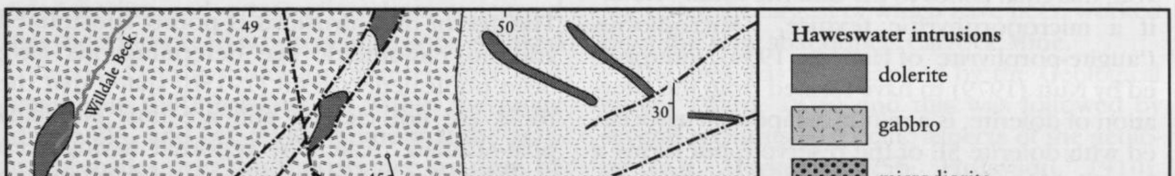

Figure 4.42 Map of the Haweswater intrusions, based on unpublished British Geological Survey maps by D. Millward and B. Beddoe-Stephens.

the NW from those within the upper part to the SE, is not supported by recent mapping of the area by the British Geological Survey (Figure 4.42); the same volcanic formations are present in both areas.

The intrusions are dominantly dolerite, with subordinate fine-grained gabbro, microdiorite, intrusive breccia and locally abundant aplitic veins. The dolerite ranges from leucocratic to melanocratic, with the more mafic rocks occurring NW of Haweswater. Leucocratic microgabbro crops out, for example, on Wallow Crag (495 151), and dolerite and gabbro on and below Wallow Crag are compositionally layered with vertical bands 2–30 cm thick. Most contacts of the intrusion with the host rocks are near vertical or vertical. Exceptions include horizontal contacts east and NE (490 145) of Kit Crag. Xenoliths are present locally within the contact zone.

North-west of Haweswater, some dolerite masses are associated with andesite along a significant fault-zone. Both NW and SE of the reservoir, marginal zones to the dolerite locally exhibit a microporphyritic texture. Microdiorite ('augite-porphyrite' of Hancox, 1934), interpreted by Nutt (1979) to have formed from the alteration of dolerite, is a minor component associated with dolerite SE of the reservoir, but forms a large body on the NW shore, south of Great Birkhouse Hill. Small garnets are a rare accessory mineral in the microdiorite.

Mineralogical alteration is moderate to intense, though original textures are preserved: most rocks are typically subophitic, intersertal or intergranular, and commonly porphyritic; locally, ophitic texture and ophimottling are present. Plagioclase is generally replaced by albite and/or mats of sericite, epidote and chlorite. Fresh clinopyroxene is present in some areas, though this is more typically replaced epitaxially by amphibole or chlorite and fibrous amphibole. Unaltered clinopyroxene in gabbros is accompanied by pseudomorphs of chlorite and/or fibrous amphibole, possibly after orthopyroxene. Interstitial quartz is common in thin-section; locally intersertal orthoclase and microperthite are present associated with micrographic intergrowths with quartz. Accessory minerals include opaque oxide, apatite, biotite and tourmaline.

Thin microcrystalline veins are abundant locally. One type comprises cloudy albite laths with amphibole, chlorite and minor secondary quartz ('doleritic aplite' of Hancox, 1934 and Nutt, 1979). Other veins consist of quartz, perthite, minor albite and accessory tourmaline ('granitic aplite' of Nutt, 1979). Hancox (1934) also described fibrous chloritic veins.

Intrusive breccia forms the marginal rocks of the faulted intrusion south of Wallow Crag (Figure 4.42). Also present is a narrow dyke on the NW shore of Haweswater (476 140). The breccia comprises fragments of dolerite and gabbro, as well as wall-rocks of andesite, rhyolite and devitrified welded tuff. The intensely altered matrix is feldspathic and andesitic. The vertical pipe of andesite breccia cutting dolerite by Low Goat Gill (506 142), SE of Naddle Beck, described by Nutt (1979, p. 729), has been reinterpreted during the recent mapping as autobrecciated andesite within the BVG country rock, capping an irregular top to the intrusion. Clasts within the breccia are wholly of andesite.

Interpretation

The age of the intrusions is poorly constrained and no radiometric age determinations have been published. Green (1915b) stated that the rocks are not cleaved and are thus implicitly post-Acadian. Later, he reported having seen samples that are cleaved, thus establishing the Early Palaeozoic age (Green, 1917). The cleavage, the regional association, and similarities in alteration styles and geochemistry with the volcanic rocks, indicated to Hancox (1934) and Nutt (1979) that the intrusions were emplaced before the regional cleavage-forming event and are Ordovician in age.

Though the Haweswater intrusions were not distinguished by the primary geological survey, Dakyns *et al.* (1897, pp. 20–21) described a dolerite, locally porphyritic and containing much augite, forming Wallow Crag and compared this with similar rocks from Measand and Colby (now submerged beneath the reservoir at *c.* 493 157), on the north side of Haweswater (Figure 4.42). Though they felt that the Wallow Crag mass is intrusive, the Measand rock was interpreted as lava.

Walker (1904) described the Haweswater mafic rocks as 'quartz-diabase' and interpreted them as intrusions; he also concluded that they are part of a large body, and similar to the lavas of Eycott Hill, which are now interpreted geochemically as tholeiitic (Fitton, 1971). Green

(1915b) used 'hypersthene-dolerite' for the Haweswater rocks, and he and Hancox (1934) both commented on the presence of orthopyroxene along with interstitial quartz and K-feldspar, characteristics that might suggest a tholeiitic affinity. However, Fitton (1971) and Nutt (1979) concluded from geochemical analyses of the intrusions that they are indistinguishable from, and thus compatible with, the calc-alkaline BVG. This conclusion does not accord with the preliminary interpretation of new, and as yet unpublished, geochemical data for the Haweswater rocks (University of Lancaster: R. Macdonald, pers. comm.), which indicate that a tholeiitic affinity is possible. If this is substantiated by further work then the dolerites cannot have been a magma chamber and vent site for the BVG. However, the Haweswater rocks do not have the high-Ti values of the tholeiitic rocks of the Eycott Volcanic Group and Carrock Fell Complex in the north (Hunter, 1980), and pre-cleavage dykes cutting the BVG and Eskdale granite in the west (Macdonald *et al*., 1988).

Surface contact exposures indicate steep-sided bodies and previous workers concurred that the widespread group of intrusions is linked at depth. Density values for representative rock types from the intrusions fall within the range for the BVG and Lee (1986) found that the gravity anomalies over the Haweswater area can be interpreted best if the mafic intrusions are underlain, at depths of as little as 1 km, by low density material, probably a granitic mass associated with the Shap granite. It is thus unlikely that a substantial body of mafic composition is present at depth in this area.

Conclusions

The Haweswater intrusions are a unique group of coarse-grained mafic and intermediate masses within the outcrop of the Borrowdale Volcanic Group and are probably Ordovician in age. The rocks are best exposed within the GCR site. The dolerite and associated rocks have been considered as a subvolcanic magma body, but this is not supported by geophysical evidence. Moreover, if studies in progress are substantiated, suggesting that the complex may be tholeiitic, then these intrusions are further examples in the Lake District magmatic province of the association between calc-alkaline volcanic and tholeiitic intrusive rocks.

GRAINSGILL, CALDEW VALLEY (NY 327 327)

S.C. Loughlin

Introduction

The Grainsgill GCR site, located within the Caldew valley in the northern Lake District (Figure 4.43), is an area of diverse geology that has been of interest to geologists for more than a century. The northernmost of only three small outcrops of the Skiddaw granite is exposed here and the contact between the granite and the highly deformed Skiddaw Group into which it is intruded is clearly demonstrated. Locally, the northern part of the granite outcrop is extensively altered to greisen. Only 100 m north of the granite margin, the Carrock Fell Complex is intruded at the boundary between the Skiddaw Group and Eycott Volcanic Group (see also the Carrock Fell GCR site report). The greisen, the hornfelsed Skiddaw Group and the Carrock Fell Complex are cut by arsenic- and tungsten-bearing veins, the largest of which have been worked from the now abandoned Carrock Mine.

The area was first mapped by the Geological Survey (Ward, 1876) and this was followed by several accounts of specific aspects of the geology (e.g. Harker, 1895b; Finlayson, 1910). Hitchen (1934) concluded that the granite, greisen and mineralization are related to one igneous episode. Field evidence also led to the deduction that the greisen formed by metasomatism of the granite and this was confirmed by subsequent studies (Thimmaiah, 1956; Ewart, 1962; Eastwood *et al*., 1968). Shepherd *et al*. (1976) used fluid inclusion and isotope techniques to suggest a genetic link between mineralization and alteration of the granite.

This GCR site provides a very important insight into the relationship between igneous intrusion, metasomatism and mineralization. In addition it contains important evidence of the timing of emplacement of the Skiddaw granite, one of only two late Caledonian intrusions in the Lake District. The mineral veins at Grainsgill will also be described in the *Mineralization of Great Britain* GCR volume.

Description

The oldest rocks in the Grainsgill GCR site are

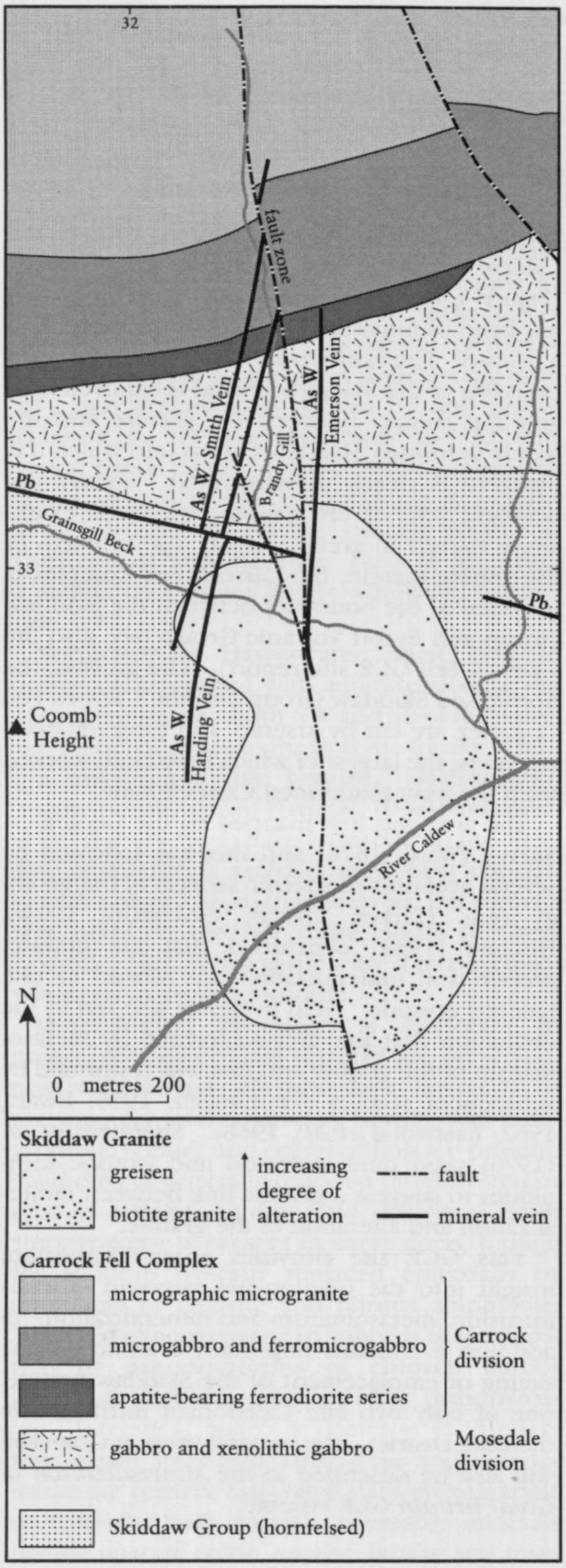

Figure 4.43 Map of the Grainsgill GCR site (from Geological Survey maps).

very strongly folded metapelites of the Skiddaw Group. Fold interference patterns suggest that several generations of deformation are present. On the sides of Carrock Fell, north of the River Caldew, the axial planes of folds are almost vertical and trend N–S, perpendicular to the contact between the Skiddaw Group and the Carrock Fell Complex. Contact metamorphism has altered rocks of the Skiddaw Group to biotite-cordierite hornfels within a classically concentric aureole 10 km in diameter. As the greisen is approached cordierite is altered to chlorite and biotite is replaced by muscovite.

The Carrock Fell Complex is a multiple dyke-like intrusion, emplaced between the Skiddaw Group and the Eycott Volcanic Group and is exposed in Brandy Gill, 100 m to the north of Grainsgill (see the Carrock Fell GCR site report for detailed description). In Brandy Gill, the southern part of the Carrock Fell Complex comprises gabbro and xenolithic gabbro of the Mosedale division, cut upstream by apatite-bearing ferromicrodiorite, ferromicrogabbro and micrographic ferromicrogranite sheets belonging to the Carrock division.

The Skiddaw granite is exposed in Grainsgill Beck and in the River Caldew (Figure 4.43); the intrusion appears to be a steep-sided dome with its long axis approximately N–S (Hitchen, 1934). It is laterally extensive at shallow depths (Lee, 1986). The contact between the intrusion and the hornfelsed sedimentary rocks is well exposed in both Grainsgill Beck and the River Caldew just upstream from their confluence. On Coombe Height, between the two rivers, Skiddaw Group rocks overlie the flat roof of the granite.

The Skiddaw intrusion is a medium-grained biotite granite comprising orthoclase, oligoclase, quartz and biotite. Accessory minerals include zircon, apatite, ilmenite, pyrrhotite, pyrite, epidote, titanite, anatase, brookite, and rutile (Rastall and Wilcockson, 1915). In the River Caldew, feldspars are partially replaced by muscovite as a result of incipient greisen formation, and the biotite is partially replaced by chlorite. The degree of greisen formation increases northwards to Grainsgill where the original biotite granite is pervasively converted to a muscovite-quartz greisen. Apatite, rutile, pyrite and arsenopyrite also occur in the greisen.

The principal rocks within the GCR site are transected by NNE-trending tungsten-bearing veins ranging in width from less than 1 cm to

1.5 m and dipping steeply to the west. Within about 60 cm of large veins and less for smaller veins, the granite is pervasively altered to greisen comprising quartz, muscovite, pyrite, arsenopyrite and apatite. The veins have also altered the cordierite-andalusite-biotite hornfels of the Skiddaw Group. Biotite is altered to chlorite and andalusite to sericite as a vein is approached and within 20–30 cm of the contact, the chlorite and sericite are altered to muscovite; pyrite and tourmaline occur in small amounts in this new assemblage. Alteration is also noticeable in the gabbros of the Carrock Fell Complex within 50 cm of the veins. Within 15 cm of a vein the gabbro is completely altered to quartz, biotite, sericite and some muscovite, and immediately adjacent to the vein the original mineralogy is replaced by arsenopyrite, pyrite, quartz, calcite and muscovite.

The largest veins worked at Carrock Mine are, from west to east, the Smith, Harding and Emerson (Figure 4.43). The dominantly quartz veins contain local pockets of wolframite, scheelite, arsenopyrite, pyrite, pyrrhotite, sphalerite and ankerite along with accessory molybdenite, chalcopyrite, bismuthinite, apatite, dolomite, calcite, fluorite, and muscovite with rare joseite, cosalite, cassiterite and gold (Finlayson, 1910; Hitchen, 1934; Ewart, 1962; Shepherd *et al.*, 1976; Young, 1987). Despite variable relative mineral proportions, all the veins have a similar paragenetic sequence (Hitchen, 1934; Shepherd *et al.*, 1976).

The two near-vertical, quartz- and ankerite-filled NNW-trending fault zones in the upper and lower parts of Brandy Gill do not appear to have hydrothermally altered the country rocks (Ewart, 1962). Narrow E–W veins carrying quartz, galena and sphalerite slightly displace the tungsten-bearing veins and are considered to be related to the extensive E–W lead and zinc veins found in the Caldbeck Fells to the north of the GCR site (Shepherd *et al.*, 1976). Two veins of 'greisen' were reported by Hitchen (1934): one of these is about 1 m wide and cuts the Carrock Fell Complex in Brandy Gill and the other cuts the hornfelsed Skiddaw Group in the upper reaches of Grainsgill. Ewart (1962) found several more of these veins underground, and suggested that they may be metasomatized aplitic veins.

Interpretation

Ward (1876) described a 'very quartzo-micaceous granite' at Grainsgill and suggested that this is part of the Skiddaw granite, because the contact between it and the biotite granite exposed in the River Caldew is gradational. Harker (1895b) recognized that the granite had undergone some metasomatism, but suggested that it formed primarily as a late-stage acid melt squeezed from the crystallizing Skiddaw granite by northerly directed pressure. Finlayson (1910) related the ore minerals genetically to the greisen. Rastall and Wilcockson (1915) noted that accessory minerals of the granite are relatively scarce in the greisen, and that minerals such as arsenopyrite are more common.

Hitchen (1934) proposed that the granite, greisen and mineralization are related to one igneous episode. He described the gradual change from biotite granite to greisen, involving the replacement of feldspars by muscovite. Where the greisen is entirely quartz and muscovite, the original outlines of feldspar crystals can still be discerned, even in hand specimen. He suggested further that the large number of mineral veins in the greisen, and the increase in abundance of arsenopyrite, indicate that intense localized hydrothermal activity had occurred. The scarcity of accessory minerals was attributed to their removal by hydrothermal fluids. Hitchen concluded that, following the consolidation of the granite, greisen was formed as a result of hydrothermal activity and aqueous solutions deposited minerals in fissures and cracks.

Subsequent work confirmed the metasomatic origin of the greisen (Thimmaiah, 1956; Ewart, 1962; Eastwood *et al.*, 1968). Thimmaiah (1956) and Ewart (1962) considered that the only true greisen in the area is the thoroughly altered granite near the quartz-tungsten veins, whereas Eastwood *et al.* (1968) also described the altered hornfels adjacent to the veins as greisen. However, geochemical studies by Roberts (1983) showed that, despite their similar appearance in the field, the metasomatized hornfels has a very different chemistry to the greisen.

A genetic link between alteration of the granite and mineralization was proposed by Shepherd *et al.* (1976) using fluid inclusion and oxygen isotope data. They found that mineral deposition and greisen formation indicate equilibration with fluids of similar isotopic compositions under similar P–T conditions. K-Ar dating could not distinguish between cooling of the

Skiddaw granite, greisen formation and tungsten mineralization (minimum age of granite intrusion, 392 ± 4 Ma; mean age of mineralization alteration, 385 ± 4 Ma) suggesting that they occurred within a relatively short space of time. Fluid inclusions in vein quartz contain NaCl brines and high tungsten concentrations occur in the altered granite of the mineralized area. Based on their data they suggested that mineralizing fluids were moderately saline with high Na/K, enriched in tungsten and periodically charged with CO_2; compared with magmatic fluids the mineralizing fluids were depleted in $\delta^{18}O$. Shepherd *et al.* (1976) produced a model of ore genesis whereby meteoric water was drawn convectively into the northern part of the Skiddaw granite through the adjacent relatively permeable igneous rocks of the Carrock Fell Complex. Chemical exchange increased the salinity of these fluids before they reached the granite where they became mixed with hot magmatic fluid enriched in tungsten. The granite was metasomatized to form greisen and the circulating fluids became enriched in silica due to the breakdown of primary igneous silicates. These fluids convected and mixed with more non-magmatic fluids along the N–S faults which cut the complex, producing the mineral veins.

Roberts (1983) proposed that leaching of the greisen and metasomatized hornfels by the circulating fluids provided the Na for the NaCl brines found in the fluid inclusions. Therefore, the initial fluid did not necessarily have high Na/K ratios. He favoured a model in which brines enriched in K due to feldspar alteration were drawn down to the intrusion and then resulted in the formation of greisen and K-metasomatism.

A recent model proposed by E. S. Burden (Derby University, pers. comm. 1996) combined fluid inclusion studies with mineralogical data and mass-balance calculations to show that greisen can form from granite simply by the addition of H_2O. The process involves a series of linked ionic sub-reactions and the alteration of K-feldspar to muscovite releases K-ions which are necessary to convert plagioclase to muscovite.

Geochemical data for the Skiddaw granite show clear magmatic trends consistent with either in-situ fractionation or derivation from a deeper fractionating magma chamber (O'Brien *et al.*, 1985). The Skiddaw granite has highly fractionated rare earth element (REE) patterns and, like the Shap granite, is thought to be derived from a mafic source containing residual garnet. It also contains elevated levels of the heat-producing radioactive elements and the geothermal potential of the granite has been assessed (Webb and Brown, 1984a; Wheildon *et al.*, 1984).

The age of emplacement of the Skiddaw granite has been discussed by several authors (Miller, 1961; Brown *et al.*, 1964; Shepherd and Darbyshire, 1981) and K-Ar dating of fresh biotite gives an age of 399 ± 8 Ma (recalculated from Shepherd *et al.*, 1976), very similar to the Shap granite (Rundle, 1982). Eastwood *et al.* (1968) showed that the hydrothermal alteration associated with the granite post-dates the Carrock Fell Complex. In the outer parts of the Skiddaw granite aureole, andalusite clearly overgrows the main cleavage indicating that contact metamorphism post-dates the Acadian deformation. However, in the inner hornfels zone of the aureole, the cleavage weakly wraps around andalusite porphyroblasts. The implication is that the granite was emplaced during the late stages of the Acadian Event, perhaps during a period of stress relaxation between successive cleavage-forming events (Soper and Roberts, 1971; Soper and Kneller, 1990; see also the Shap Fell Crags GCR site report).

Conclusions

The late Caledonian Skiddaw granite shows a clear northwards gradation from biotite granite to greisen and it can be shown that hydrothermal alteration associated with emplacement of the granite was also responsible for the greisen formation and the deposition of some economically important mineral veins. The nearby intrusive Carrock Fell Complex provided a permeable pathway for fluids to circulate down towards the granite and explains why metasomatism and mineral deposition are concentrated only in the northern part of the Skiddaw granite. The Grainsgill GCR site is significant because it provides an important insight into the relationship of a late Caledonian intrusion to greisen formation and mineralization. The site also provides important evidence regarding the timing of emplacement of late Caledonian intrusions in the Lake District.

SHAP FELL CRAGS (NY 555 084)

S.C. Loughlin

Introduction

The Shap Fell Crags GCR site comprises the Shap Pink Quarry and is the principal exposure of the Shap granite, renowned as a distinctive, decorative building stone. The igneous processes that can be demonstrated within the quarry make this an internationally significant site. The site (Figure 4.44) has been a popular field locality for undergraduate students and amateur geologists for many years. The granite and its associated metasomatism and mineralization have been described by many authors (e.g. Harker and Marr, 1891, 1893; Rastall and Wilcockson, 1915; Grantham, 1928; Firman, 1957, 1978a, 1978b) and it is featured in numerous classic geological textbooks (e.g. Teall, 1888; Hatch *et al.*, 1971; Holmes, 1993).

The origin of the abundant pink Carlsbad-twinned K-feldspar megacrysts, which are the trademark of the Shap granite, has been a source of much controversy. The megacrysts occur not only in the granite but also within microgranular mafic enclaves within the granite, leading to the suggestion that the megacrysts are porphyroblasts resulting from late-stage crystallization from potassium-rich metasomatic fluids (Vistelius, 1969; Firman, 1978b; Le Bas, 1982a). However, recent work favours a phenocrystic origin for the megacrysts (e.g. Vernon, 1986; Lee *et al.*, 1995; Cox *et al.*, 1996; Lee and Parsons, 1997).

The intrusion is steep sided, and was emplaced close to the boundary between the Borrowdale Volcanic Group and the Windermere Supergroup (Locke and Brown, 1978). Radiometric dates obtained by a number of methods indicate an Early Devonian age (Pidgeon and Aftalion, 1978; Wadge *et al.*, 1978; Rundle, 1992). The granite was originally thought to post-date Caledonian deformation (Boulter and Soper, 1973), but recent field evidence proves that it was emplaced during, not after, the late Caledonian Acadian Event (Soper and Kneller, 1990). Thus, the granite is crucial in dating Caledonian deformation events within the Lake District.

A geochemical study of the Shap granite was made by O'Brien *et al.* (1985). Elevated levels of the radioactive elements U, Th, Rb and K explain the high present-day heat production of the granite which has been investigated as a potential source of geothermal energy (Wheildon *et al.*, 1984).

Description

Grantham (1928) recognized that the Shap granite was formed in three stages. To the west of the quarry, near Wasdale Head Farm (549 081), is a grey granite ('stage' I) which grades up into, and is transgressed by, the familiar pink, coarse-grained granite ('stage' II) which occupies up to 90% of the intrusion. The 'stage' III granite is less common and cuts the earlier mass in dyke-like bodies between 1 cm and 1 m wide.

The 'stage' I granite contains about 15% pink, Carlsbad-twinned orthoclase-perthite megacrysts up to 5 cm in length. The groundmass is composed of orthoclase, plagioclase zoned from andesine to albite, quartz, and biotite. By contrast, the 'stage' II granite contains less biotite and up to 30% pink K-feldspar megacrysts which commonly show a preferred alignment. The 'stage' III granite is very similar in appearance to the 'stage' II granite, but contains up to 60% pink K-feldspar megacrysts and has even less biotite. Accessory minerals include titanite, apatite, magnetite, zircon, fluorite, monazite, allanite, amphibole and pyrite (Firman, 1978b). Complex microtextures in the megacrysts have been described by Lee *et al.* (1995), Cox *et al.* (1996) and Lee and Parsons (1997). The megacrysts also contain numerous inclusions of plagioclase, biotite and quartz that increase in size and abundance towards the rim.

The 'stage' I and 'stage' II granites contain abundant enclaves (Figure 4.45). Most common are rounded, microdioritic enclaves comprising fine- to medium-grained aggregates of plagioclase, quartz, biotite and K-feldspar. Slightly rounded, pink K-feldspar megacrysts with oligoclase rims may constitute 5–8% of the enclaves; some of these megacrysts occur partly within the enclave and partly within the granite host. Clots of granite matrix up to 1.5 cm across have been reported from within some enclaves (Cox *et al.*, 1996). In addition, the 'stage' II granite contains enclaves of 'stage' I granite that range from only a few centimetres across to rafts with dimensions of 36 × 30 × 6 m (Grantham, 1928). Identifiable xenoliths of hornfelsed andesitic

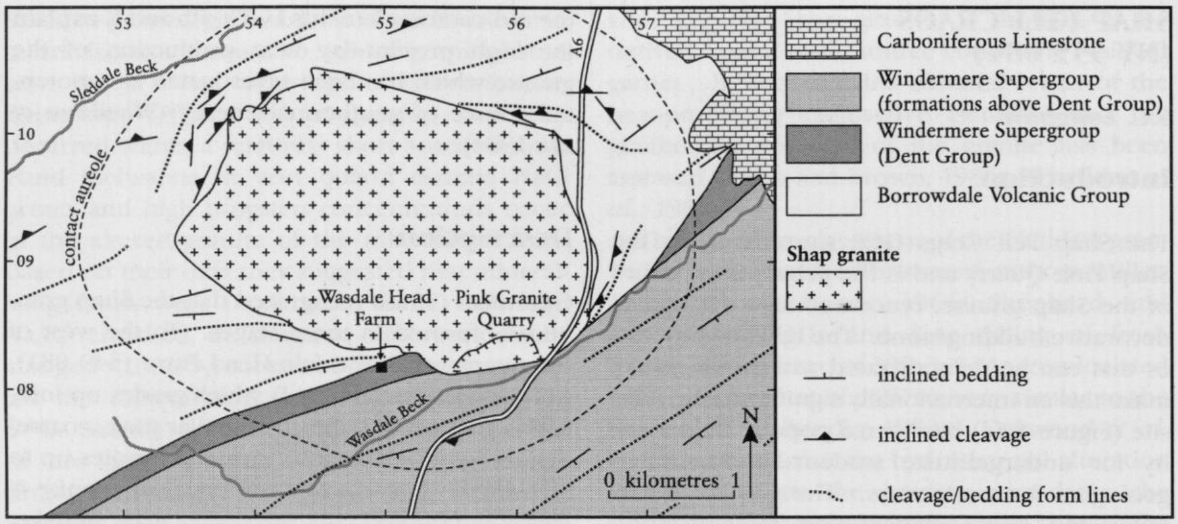

Figure 4.44 Map of the Shap Fell Crags GCR site (after Soper and Kneller, 1990).

rocks from the Borrowdale Volcanic Group occur near the margins of the intrusion. Xenoliths of Dent Group lithologies (formerly the Coniston Limestone) were abundant near the southern contact of the intrusion, but are now rare because quarrying has advanced away from this contact. Harker and Marr (1891) noted that K-feldspar megacrysts do not occur in 'xenoliths formed from solid rock fragments'.

Aplitic veins are common within the granite and country rocks, and pegmatitic rocks are common locally; both contain quartz, K-feldspar and a little plagioclase. Molybdenite and hydrothermal vein minerals coat many surfaces within a pervasive, blocky joint system. Two distinct vein assemblages are seen: the first contains quartz, calcite, bismuthinite and chalcopyrite, and the later veins contain quartz, calcite, haematite, fluorite and baryte. These veins commonly penetrate the centre of 'stage' III granite bodies giving the orthoclase on either side of the vein a deeper pink colour. Where such veins cut the 'stage' II granite, darkening of the feldspars may occur up to 5 m from the vein giving rise to the 'Dark Shap', a highly prized variety of the Shap granite that is difficult to extract. 'Light Shap' refers to the normal unaltered pink variety of granite.

Though the Shap granite outcrop is small (*c.* 5 km^2), gravity data (Lee, 1986) and contact metamorphism suggest that it extends at shallow depths at least 10 km farther to the NW. Andesite and tuff within the metamorphic aureole have been converted to biotite hornfels with some amphibole in places. The more aluminous sedimentary rocks of the Windermere Supergroup may contain sillimanite, andalusite and cordierite. The country rocks are folded and faulted and a near-vertical cleavage is deflected around the Shap granite (Figure 4.44; Boulter and Soper, 1973; Soper and Kneller, 1990). At several localities in the volcanic rocks of the metamorphic aureole, biotite has clearly overgrown the cleavage (Boulter and Soper, 1973). The granite has an associated dyke swarm which is crudely orientated NE–SW, sub-parallel to the Acadian folding and faulting.

Interpretation

Early researchers proposed that the K-feldspar megacrysts in the Shap granite are phenocrysts (Harker and Marr, 1891; Grantham, 1928), though others preferred a porphyroblastic origin (Vistelius, 1969; Le Bas, 1982a). However, modern microtextural, geochemical and isotopic analysis favours a phenocrystic origin (Vernon, 1986; Lee *et al.*, 1995; Cox *et al.*, 1996; Lee and Parsons, 1997). Features cited as evidence for this theory include the following:

1. The apparent alignment of some megacrysts.
2. The higher Ba content in K-feldspar megacrysts than in K-feldspar in the groundmass suggesting earlier crystallization.

Figure 4.45 Pink granite with xenoliths containing K-feldspar megacrysts. (Photo: D. Millward.)

3. Chemical and isotopic zoning of the megacrysts consistent with growth in a magma body.
4. Inclusions in the megacrysts which increase in size and frequency towards the rim suggesting that the megacryst and inclusions were growing simultaneously in a magmatic environment.
5. The typically euhedral inclusions exhibit zonal alignment implying growth in a magmatic environment.

Evidence for a porphyroblastic origin is the occurrence of megacrysts within the microdioritic enclaves and, more importantly, in some examples transgressing the margins of enclaves. The scarcity of K-feldspar in the groundmass and clear evidence of metasomatism prompted several authors to suggest that late-stage potassic metasomatic fluids circulated through the granite causing porphyroblastic growth of orthoclase (Vistelius, 1969; Firman, 1978b; Le Bas, 1982a).

The microdioritic enclaves were termed the 'Early Basic Granite' by Grantham (1928), who proposed that they represent an early peripheral hybrid granite. Grantham considered xenoliths of hornfelsed Borrowdale Volcanic Group rocks to be very rare except at the margins of the intrusion, whereas Firman (1978b) suggested that most enclaves represent material from the Borrowdale Volcanic Group at varying stages of recrystallization and assimilation. Recent work suggests that the enclaves formed during mixing between a dioritic magma and the host granite, and that some megacrysts may have been incorporated into the dioritic magma during that process (Vernon, 1986; Cox *et al*., 1996). This mechanism may account for the slightly rounded appearance of the megacrysts and the oligoclase rims, which are absent from megacrysts in the granite. Some K-feldspar megacrysts at the boundary between granite and microdiorite enclaves contain shells of inclusions that are difficult to explain if the megacrysts are porphyroblasts (Vernon, 1986). In discussion of this problem Vernon (1986) also cited the rare occurrence in granites elsewhere of xenoliths as well as megacrysts transgressing the boundary of an enclave. He considered this as evidence of their incorporation before solidification.

Based on geochemistry, O'Brien *et al.* (1985) showed that the Shap granite is unlikely to have been generated from a sedimentary source such as the Skiddaw Group, despite having moderately high initial $^{87}Sr/^{86}Sr$ values of 0.707 (Wadge *et al.*, 1978) and high $\delta^{18}O$ of +11.0‰ (Harmon and Halliday, 1980). The Skiddaw Group sedimentary rocks contain particularly high concentrations of boron and on mantle-normalized plots show a pronounced negative phosphorous anomaly; neither of these features is a characteristic of the Shap granite. It is calc-alkaline with a restricted composition. High levels of large-ion lithophile (LIL) elements in the Shap granite suggest that it is magmatically evolved, but compatible elements such as Mg, Cr, Ni, Ti, V, Sr and Ba show no evidence for an extended history of crystal fractionation. Changes in fluid content or pressure, and partial hybridization appear to have dominated the geochemical evolution of these rocks. It is unclear to what extent metasomatism might have fundamentally increased LIL concentrations, though the mobility of K and Rb during metasomatism has been recognized for a long time (e.g. Vistelius, 1969). O'Brien *et al.* (1985) proposed that the Shap granite was the site of discharge of high-temperature fluids from depth thus explaining high concentrations of Li (Farrand, 1960) and other incompatible elements such as Rb.

O'Brien *et al.* (1985) also showed that the Lake District granites as a whole have increasingly fractionated rare earth element patterns with time. The Shap granite has the most fractionated REE pattern and also the highest La/Yb suggesting that it was derived from a mafic source containing residual garnet. Ordovician (Caradoc) Lake District granites with lower La/Yb were derived from a source without residual garnet, perhaps reflecting changing thermal conditions during magma generation (O'Brien *et al.*, 1985). The younger, Early Devonian granites of Shap and Skiddaw contain higher abundances of radioactive elements than the other Lake District granites. Spears (1961) recognized that 95% of the alpha radioactivity in the Shap granite comes from accessory minerals (e.g. titanite, monazite and zircon).

It has long been assumed that emplacement of the Shap granite post-dated the main Acadian deformation event, because contact metamorphic minerals have overgrown cleavage within the metamorphic aureole of the granite (Boulter and Soper, 1973). However, some felsitic microgranite dykes within the Shap dyke-swarm, which cut folded and cleaved Silurian sedimentary rocks, are themselves weakly cleaved, implying that the dykes were emplaced during cleavage formation (Soper and Kneller, 1990). Some of these cleaved dykes cut the Shap granite and therefore the granite itself may also have been emplaced during the cleavage-forming event. Boulter and Soper (1973) interpreted the deflection of the cleavage around the Shap granite as having resulted from the forcible injection of the intrusion. However, it is also possible that the cleavage 'wraps' around the granite because shortening continued after the granite was emplaced (Figure 4.44; Soper and Kneller, 1990). Soper and Kneller inferred from this evidence that the cleavage formed incrementally, with periods of stress relaxation allowing the injection of dykes and possibly the emplacement of the granite itself.

The age of the Shap granite is therefore crucial in determining the timing of cleavage formation. Using K-Ar and Rb-Sr methods on biotite, several early authors dated the Shap granite as late Silurian or Early Devonian (Kulp *et al.*, 1960; Lambert and Mills, 1961; Dodson *et al.*, 1961). In a study of these and other available isotopic dates, Brown *et al.* (1964) recognized that the Shap granite is coeval with the Skiddaw granite. More recently, three separate radiometric dating methods have produced similar dates: U-Pb on zircons gave an age of 390 ± 6 Ma (Pidgeon and Aftalion, 1978); 394 ± 3 Ma was obtained using the mineral–whole-rock Rb-Sr isochron (Wadge *et al.,* 1978), but it is the K-Ar age of 397 ± 7 Ma on fresh biotite that is taken to indicate the age of emplacement of the Shap granite (Rundle, 1992). These conclusions are consistent with the age of cleavage formation of between 418 ± 3 Ma and 397 ± 7 Ma recently obtained on mica concentrates from the Foredale metabentonite in the Ribblesdale inlier (Merriman *et al.*, 1995). Thus, Acadian deformation in northern England occurred in the Early Devonian, some 23 Ma after Silurian deformation in the Southern Belt of the Southern Uplands (*c.* 420 Ma, Barnes *et al.*, 1989).

Conclusions

The Shap granite is a widely used decorative building stone whose principal outcrop is within the Shap Fell Crags GCR site. This internationally significant site illustrates several important features that are crucial to the continuing debate concerning the magmatic evolution of granites and their large K-feldspar crystals. The 397 Ma Shap granite, its metamorphic aureole and dyke-swarm provide crucial evidence in the determination of the sequence and timing of the late Caledonian, Acadian Event in the Lake District. Field evidence suggests that the deformation was episodic and that the granite and the associated dyke swarm were emplaced during periods of stress relaxation.