

Lake District Batholith, Caradoc magmatism, Ordovician, Northern England

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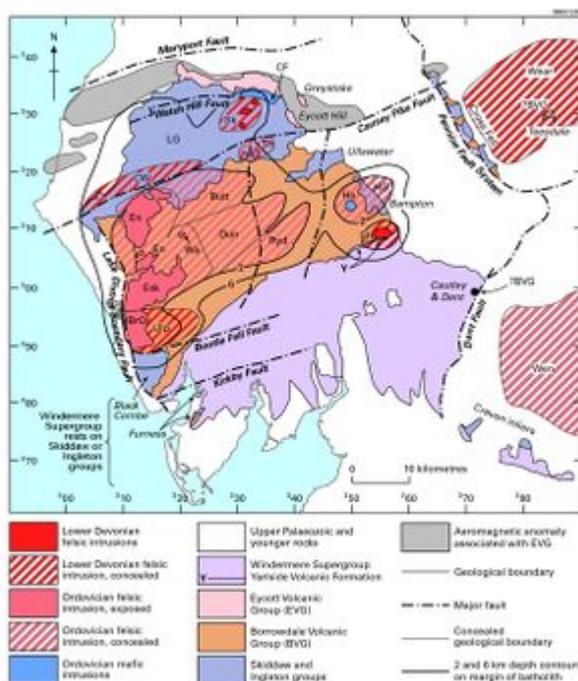
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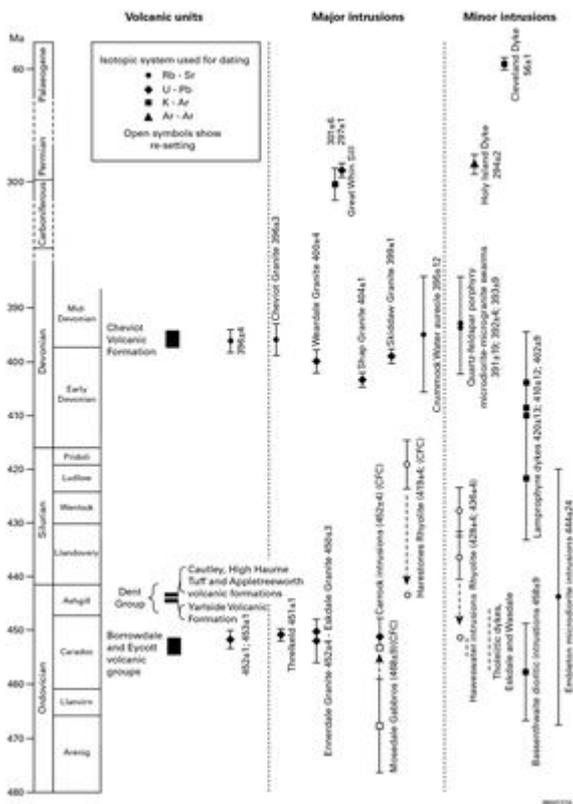
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Emplacement (P916111), phase 10



Geological map showing the principal Ordovician and Devonian igneous bodies

and their relationship to major structural features. BrO Broad Oak Granodiorite Pluton, Butt Buttermere Intrusion, CF Carrock Fell Centre, CW Crummock Water Granite, Dun Dunmail Intrusion, En Ennerdale Granite Pluton, Esk Eskdale Granite Pluton, Ha Haweswater Gabbro-Microdiorite Swarm, HG Haweswater intrusion, LG Loweswater Intrusion, Ryd Rydal Intrusion, Sh Shap Granite Pluton, Sk Skiddaw Granite Pluton, Th Threlkeld Microgranite Intrusion, Ulp Ulpha Intrusion, Wa Wasdale outcrop of Esk, Wear North Pennine Batholith, Wen Wensleydale Granite Pluton. P916043.



Summary chart of radiometric dates for the igneous rocks of northern England. P916034.

Outcrops of the major granitic intrusions in the Lake District, including the Ennerdale, Eskdale, Broad Oak and Threlkeld masses have long been known in detail, but it was the pioneering interpretations of gravity anomalies that linked these surface exposures to large concealed granitic masses underlying northern England. The subsurface extent of the Lake District Batholith is more than 1500 km² and detailed interpretation of the potential-field data permits recognition of a substantial number of components ([P916043](#)).

Seismic reflection profiles across the western margin of the batholith exhibit zones of intense, subhorizontal reflections intercalated with lenticular, nonreflective ones; these are interpreted respectively as Skiddaw Group hornfels and granitic sheets. The western margin of the stacked, tabular granite sheets has a saw-tooth-like form, and is broadly coincident with the Lake District

Boundary Fault.

Caradoc radiometric ages for the exposed Ennerdale, Eskdale and Broad Oak intrusions suggest that the postulated concealed batholith components beneath were also emplaced during this time ([P916034](#)). These intrusions also broadly underlie the Scafell Caldera. The batholith is divided by a narrow 'neck' that coincides with the Troutbeck Fault Zone. To the east, there are two bodies, the Haweswater and Shap granites. The former may also be Ordovician, because it underlies a caldera-related pyroclastic succession around Haweswater, but the latter is Devonian and so unrelated to the Ordovician volcanism.

The timing of emplacement of the major plutons relative to the volcanic rocks is not known. However, injection of a stack of tabular granite sheets must have uplifted the volcanic sequence substantially, perhaps causing the present relationship across the Thistleton Fault, where possibly the youngest rocks of the Gosforth succession are juxtaposed against the Birker Fell Formation. Within the volcanic sequence, evidence for episodes of substantial uplift is sparse. Uplift centred on the Helvellyn area prior to eruption of the Lincomb Tarns ignimbrites has been inferred, but this is not spatially associated with the granite 'highs' in the western and eastern Lake District. Further, the rhyolite volcanoes at Scafell and Haweswater appear not to have undergone late-stage resurgence due to the injection of later magma bodies, a typical phenomenon at some large silicic caldera volcanoes worldwide. Evidence for substantial uplift during emplacement of the Borrowdale Volcanic Group is generally lacking and it must be concluded that injection of the granites occurred late in the magmatic cycle.

Renewed marine sedimentation (P916111), phase 11

This scenario provides a mechanism for erosion of the volcanic pile prior to the onset of Dent Group sedimentation. In the eastern Lake District, topographical relief of several hundreds of metres is present on the upper surface of the Borrowdale Volcanic Group, but very low relief is present south-west of Ambleside, where the unconformity appears to cut down progressively through almost 3000 m of the volcanic succession. During late Ordovician time, global sea levels were falling and a marine transgression at this time in north-west England, marked by the base of the Dent Group, must have had a local cause. To the north and east of the Lake District, in the Carrock and Cross Fell areas respectively, marine sedimentation began with the Drygill and Dufton Shale formations of Longvillian age, but in the Lake District, onset of sedimentation was at least 2 Ma later, in Cautleyan times. Thermal contraction of the batholith and the subvolcanic lithosphere as they cooled following cessation of magmatism provides a local mechanism for controlling the marine transgression.

Ennerdale Microgranite Pluton (452 +/- 4 Ma, U-Pb, zircon)

The Ennerdale Pluton, commonly known as the Ennerdale Granophyre, is a 1-2 km-thick, tabular body that crops out over 53 km² in the western Lake District, north-west of Wast Water. This mass intrudes the Skiddaw and Borrowdale Volcanic groups and may be faulted against the Eskdale Granite. Porphyritic granophyric granite dominates, but dolerite, dioritic, and hybridised dioritic, granodioritic and melanocratic granitic rocks occur locally, adjacent to the margin of the intrusion. The dolerite possibly represents sidewall cumulates from crystallisation of an early dioritic magma, but emplacement of the more voluminous granitic magma whilst the former was still hot and partly crystallised led to the local formation of hybrid rocks.

Eskdale Granite Pluton (450 ± 3 Ma, U-Pb, zircon)

The Eskdale Granite has an outcrop of 53 km² and consists of medium-grained muscovite granite, aphyric and megacrystic microgranite, and coarse to very coarse granite. Microgranite is most common in the northern part where the almost horizontal marginal contacts and inliers of hornfelsed volcanic rocks suggest that the roof zone of the intrusion is exposed. It is almost concordant with the base of the Birker Fell Formation, but rises in the northern part of its outcrop, at Wasdale Head ([P916043](#)), to within a few hundred metres of the base of the Scafell Caldera succession.

Metasomatic recrystallisation to quartz-white mica and quartz-topaz greisens occurs locally within all facies except the coarse granite. A distinctive quartz-andalusite rock is associated with topaz-greisen adjacent to the contact with the Skiddaw Group near Devoke Water.

Minor mineralisation is associated with the greisens around the Eskdale Granite. Small concentrations of arsenopyrite, native bismuth, bismuthinite and molybdenite occur disseminated through parts of the topaz-greisen at Water Crag, near Devoke Water. Coarsely crystalline specular haematite occurs locally as vein-like segregations.

Broad Oak Granodiorite Pluton

The Broad Oak Granodiorite (previously referred to, rather confusingly, as the Eskdale Granodiorite) is a discordant mass, 23 km² in area, which cuts rocks of the Duddon Basin succession. It is medium grained, with hornblende and, locally, almandine garnet and abundant biotite; it lacks muscovite.

There is a marginal microgranodiorite. In the south, the granodiorite displays strong argillic alteration. Its emplacement age relative to the Eskdale Granite cannot be determined because their contacts are not exposed. The granodiorite is considered to be Ordovician and its Wenlock Rb-Sr age of 429 ± 22 Ma to be reset; such resetting is a common feature of both the Ordovician intrusions and rocks of the Borrowdale Volcanic Group (see [Acadian Orogeny, Devonian, Northern England](#)).

Threlkeld Microgranite Intrusion (451 ± 1.1 Ma, U-Pb, zircon)

Interpretation of gravity anomalies east of Keswick has shown that the outcrops of garnet-bearing microgranite are connected to a largely concealed laccolith, 500–1000 m thick and approximately 12 km² in area, that lies above the main part of the batholith. The Threlkeld Microgranite was intruded into the Skiddaw Group and basal part of the Borrowdale Volcanic Group. The rock contains microphenocrysts of albite and orthoclase, and phenocrysts of corroded quartz and sporadic almandine garnet. The geochemistry and style of the sericite, carbonate and chlorite alteration are very similar to that of silicic pyroclastic rocks in the volcanic group, suggesting that both rock groups were altered at the same time and under similar conditions.

Carrock Fell Centre

The Carrock Fell Centre was emplaced at the junction between the Skiddaw and Eycott Volcanic groups and comprises mafic, mafic-felsic and felsic intrusions with distinctive geochemical affinities. The earliest intrusions are layered cumulate rocks of the Mosedale Gabbros, which form the southern part of the centre. They were intruded as sub-horizontal sills at the base of the cogenetic volcanic group. However, the K-Ar biotite age of 468 ± 9 Ma for the gabbros does not accord with the probable Caradoc age for the volcanic rocks.

Cutting the Mosedale Gabbros with near-vertical, intrusive contacts are the Carrock Intrusions

(452.4 ± 3.1 Ma, U-Pb, zircon). These comprise a main mass of micrographic microgranite, known as the Carrock Granophyre, with a narrow zone of apatite-bearing iron-rich microdioritic rocks along the southern margin, intruded by a comagmatic dyke-like body of microgabbro. Typically, the microgranite comprises zoned albite-oligoclase phenocrysts within micrographic intergrowths of quartz and alkali feldspar, and interstitial spherulitic intergrowths. There are small amounts of Ca-rich pyroxene, amphibole and titanomagnetite. The microgranite is interpreted to represent the subsided roof zone of a near-vertical magma chamber in which crystal fractionation of low-Mg tholeiitic basaltic magma had occurred.

Later, lenticular intrusions of micrographic microgranite were emplaced along the Roughton Gill Fault, at the western extent of the complex. The last intrusion at Carrock Fell was the quartzphyric Harestones Rhyolite. This was emplaced into, and bleached, the Longvillian Drygill Shales now seen within a fault-slice along the northern margin of the complex. The Harestones Rhyolite has a late Silurian Rb-Sr isochron age (419 ± 4 Ma), but it is suspected that this has been reset and that the rhyolite belongs to the Ashgill phase of magmatism. Some geochemical similarities with the Yarlside Volcanic Formation support such an association.

Minor intrusions

Many dykes and small intrusive masses of basaltic, andesitic and rhyolitic composition are associated with the magmatism. Aphyric basalt, andesite and microdiorite masses comprising the Embleton Microdiorite Intrusions are clustered across the Watch Hill Fault, east of Cockermouth, and were probably cogenetic with the Eycott Volcanic Group. Also within the Skiddaw Group, the more widely distributed calc-alkaline, augite-phyric meladiorite, dolerite and olivine-augite hornblendite bodies of the Bassenthwaite Intrusions are geochemically related to the Borrowdale Volcanic Group. The Wasdale Swarm comprising tholeiitic basalt dykes is mainly centred in Wasdale and Eskdale, around the margin of the Eskdale Granite.

In the eastern Lake District, over an area of 19 km², the Haweswater Intrusions comprise small plugs and dykes of hornblende-bearing dolerite and gabbro, with subordinate microdiorite. The rocks are geochemically similar to the Borrowdale volcanic rocks. There is no evidence to indicate that these intrusions are linked to a major basic mass at depth; to the contrary, the gravity low over the region indicates a concealed shallow granitic body.

The mixed-magma, composite basalt-andesite dykes and small masses of the Pike de Bield Intrusions are concentrated in the area between Scafell and Bowfell. They represent a magma conduit system that exploited pre-existing volcanotectonic faults. The intrusions cut formations up to the Esk Pike Formation, the youngest unit in the area. Contact relationships of some masses within the Seathwaite Fell Formation indicate that the host sediments were not fully lithified at the time of emplacement.

Garnet-bearing dacite dykes in Eskdale and Wasdale were probably coeval with the Scafell Dacite, a lava dome erupted during the final phase of activity at the Scafell Caldera. Pink, aphyric and sparsely microporphyrific rhyolite dykes are locally abundant adjacent to the Eskdale and Ennerdale intrusions. Geochemical similarities with the Ennerdale Microgranite suggest that, like the latter, their Rb-Sr isochron ages of 436 to 428 Ma have been reset.

Petrogenesis

Despite mineralogical and geochemical changes resulting from hydrothermal alteration and low-grade metamorphism, an understanding of the likely types of process involved in the generation and

evolution of the magmas has emerged during the last thirty years. The geochemical characteristics of the Eycott Volcanic Group rocks are transitional between medium-K, calc-alkaline and tholeiitic affinities, whilst the Borrowdale volcanic rocks are medium to high-K and calc-alkaline. Both groups have geochemical signatures that are closely analogous to modern orogenic andesite suites emplaced through thick continental crust. The range of mafic magmas present is considered to have been derived by partial melting of a common lithospheric mantle source, enriched to different levels in incompatible elements by subduction-derived aqueous fluids. Subsequent geochemical divergence into suites with tholeiitic, calc-alkaline and transitional affinities resulted from varied amounts of partial melting, different fractionation assemblages and from the assimilation of minor amounts of crustal material.

The Threlkeld and Ennerdale granites, the Broad Oak Granodiorite and associated minor intrusions have similarities with the silicic volcanic rocks which they underpin, and exhibit continental-margin volcanic-arc geochemical signatures. By contrast, many of the distinctive features of the Eskdale Granite are more typical of granites with sedimentary protoliths ('S-type'), including a restricted high-SiO₂ content, peraluminous composition, the presence of muscovite, and specific Sr and O isotope compositions. Given that these granitic rocks were emplaced in close proximity and during a very short period in Caradoc times, the compositional differences must relate to processes such as the amount of crustal material assimilated and differing crystal fractionation histories.

P916111 Summary of the principal phases in the development of the Borrowdale Volcanic Group.

Development phase	Location, lithofacies and thickness	Main events
11 Marine transgression	Post-BVG Marginal to Lake District in late Caradoc times; S Lake District in Ashgill	Thermal contraction of granites on cooling allowed progressive marine transgression on to Lake District block
10 Batholith emplacement	Beneath Scafell and Haweswater calderas. Granite, microgranite and granodiorite	Injection of thick tabular granite sheets resulting in uplift and erosion of volcanic field
9b Cross Fell	Cross Fell Inlier. Volcaniclastic sedimentary and pyroclastic rocks, one major sheet of silicic lapilli-tuff; >1100 m	Volcaniclastic sedimentation interspersed with sporadic pyroclastic eruptions
9a Gosforth succession	West Cumbria: stratiform sequence of andesitic and dacitic lapilli-tuff with subordinate volcaniclastic sedimentary rocks and andesite sills; >2500 m	Dominantly explosive intermediate and silicic pyroclastic activity producing many densely welded ignimbrites; ?caldera related
8 Helvellyn Basin succession	Central Fells, Helvellyn Basin. Stratiform units of volcaniclastic sandstone and breccia; subordinate pyroclastic units and a silicic lava; >1600 m	Fluviolacustrine sedimentation within extensional basin with episodic catastrophic influx of eruption-generated sediment-gravity flows; interrupted by small andesite lava shields and ignimbrite emplacement
7 Lincomb Tarns ignimbrite	Throughout BVG. Eutaxitic and parataxitic dacitic lapilli-tuff; columnar jointed; >800 m	Most widespread and voluminous ignimbrite within BVG. Large magnitude silicic pyroclastic eruptions forming ignimbrite shield

6	Ambleside Basin succession	Central south Lake District. Oversteps 5a, b, 4a; bedded volcanoclastic sandstone and breccia; >1100 m	Fluviolacustrine sedimentation dominated by catastrophic influx of eruption generated sediment-gravity flows. ?Associated with emplacement of many sills
5b	Kentmere Basin succession	SE Lake District. Bedded units of volcanoclastic sedimentary rocks, intercalated with sheets of pyroclastic rocks, some lavas; <2800 m	Intermediate to silicic ignimbrites; andesitic tuff-cone and lava-shield; fluviolacustrine sedimentation at base; major centre for sill emplacement
5a	Duddon Basin succession	SW Lake District. Stratified sequence of volcanoclastic sedimentary rocks, andesitic and rhyolitic pyroclastic rocks and andesite lavas	Explosive intermediate ?caldera-related pyroclastic eruptions; succeeded by catastrophic eruption-generated sedimentation in extensional basin, episodically interrupted by emplacement of silicic ignimbrites. Many sills emplaced?
4b	Haweswater Caldera succession	Ullswater, Haweswater. Stratified sheets of dacitic and rhyolitic pyroclastic rocks; garnetiferous; <650 m	Large magnitude silicic pyroclastic activity; large-volume ignimbrites associated with caldera collapse
4a	Scafell Caldera succession	Central Fells. Stratified sheets of andesitic, dacitic and rhyolitic pyroclastic rocks; dacite and rhyolite lavas; garnetiferous. Overlain by bedded volcanoclastic sandstone and breccia; >700 m	Andesitic phreatoplinian eruption followed by sequence of large volume silicic ignimbrites with associated development of piecemeal hydrovolcanic caldera; postcaldera silicic lavas and caldera basin sedimentary infill
3	Monogenetic andesite volcanoes	Throughout BVG. Andesite lavas and sills, some of basalt, basaltic andesite and dacite; subordinate tuff, lapilli-tuff and sandstone; some units garnetiferous; <2700 m	Construction of subaerial, multiple-vent, low-profile andesite volcanoes; some high volume basalt lava-fields; episodic silicic volcanism including possible caldera formation
2	Initial phreato-magmatism	Devoke Water, Calder Bridge, Millom Park, Ullswater. Mafic lapilli-tuff and tuff-breccia; contains much mudstone and sandstone from Skiddaw Group; <600 m	Hydrovolcanism, construction of tuff-cone field(s)
1	Pre-volcanic	Latterbarrow Sandstone and Overwater Siltstone locally preserved; 0-400 m	Regional uplift and erosion of Skiddaw Group. Local evidence of fluvial and ?marine deposition

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