

Garnet-Bearing Magmatism in the Palaeozoic Caledonides of Northern England

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INTRODUCTION.

Recent collaboration between the Complutense University of Madrid and the British Geological Survey investigated the renowned fluid-deposited graphite occurrence at Borrowdale in Cumbria, UK, one of only two such deposits worldwide known to be hosted by volcanic rocks. Our research has shown that one of the key factors controlling massive graphite deposition in volcanic settings is the unusually high carbon content of the magmas, resulting from the assimilation of carbonaceous metasedimentary rocks. Compelling evidence for the involvement of pelitic material in the geochemical evolution of the volcanic rocks of the Lake District also comes from the presence of almandine–pyrope garnet phenocrysts and by the study of the isotopic and trace-element compositions of bulk rock and phenocrysts. The Ordovician Borrowdale Volcanic Group is thus not only an unusual host to a large deposit of graphite, it is one of only a handful of igneous suites worldwide to contain garnet.

This paper provides a summary of the Palaeozoic magmatic history of northern England resulting from 20 years of systematic resurvey and multidisciplinary investigations by the British Geological Survey and its collaborators; the conference presentation will examine the role that assimilation of pelitic material has played in the evolution of the Palaeozoic magmas in northern England. High-precision U-Pb zircon dates provide a robust framework for the magmatic history of the region (Millward & Evans, 2003).

GEOLOGICAL SETTING.

The early Palaeozoic history of northern England is closely linked with the geological evolution of Eastern Avalonia. In early Ordovician times, this microcontinent rifted from Gondwana, drifted northwards during closure of the Iapetus Ocean and collided with Laurentia and Baltica during the Silurian period (Soper et al., 1992). Igneous rocks contributed very significantly to crustal growth in northern England and the English Midlands particularly during Ordovician and Devonian times. During late Ordovician times voluminous subduction-related volcanic and intrusive rocks were emplaced at the margin of the microcontinent in a zone extending at least from Ireland, through the Lake District and the Midlands, to Belgium (Fig. 1) as a result of closure of the

Iapetus Ocean and Tornquist Sea (Pharaoh et al., 1993). Further granitic plutons were then emplaced across the Iapetus Suture Zone towards the end of the Early Devonian, Acadian Orogeny. The buoyancy effect of these granitic masses was to have a profound effect on the later development of Carboniferous and Permo-Triassic extensional basins in northern England and provided the driving force for the emplacement of the extensive orefields of the region.

In northern England during early Ordovician times, more than 5 km of deep marine turbidites were laid down in a fore-arc basin on the northern margin of Avalonia (Cooper et al., 1995). These strata, belonging to the Skiddaw Group, were uplifted and eroded prior to a brief episode, no more than 5 Ma, of

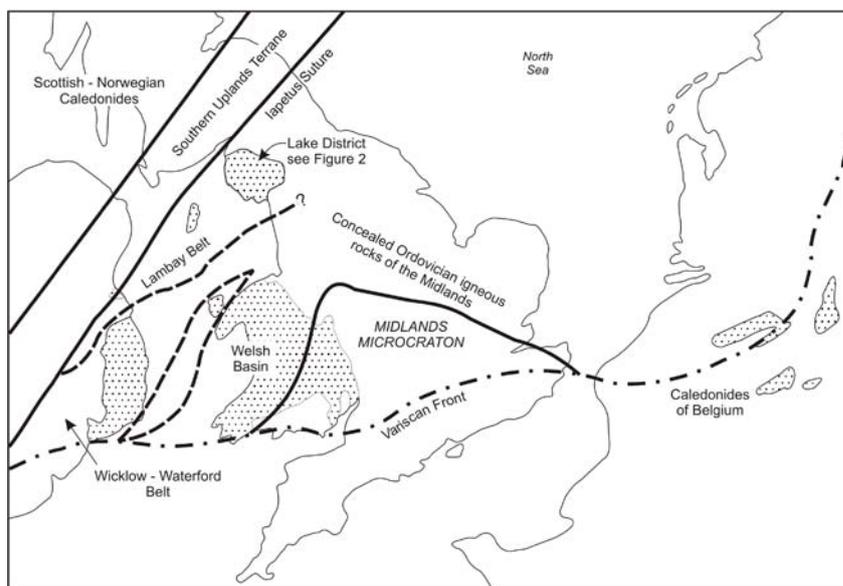


fig 1. Location map of the main occurrences of Lower Palaeozoic rocks along the margin of Eastern Avalonia from Ireland to Belgium. The Iapetus Suture marks the junction between Eastern Avalonia and Laurentia. From Millward & Evans (2003).

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subaerial subduction-related volcanism (Eycott and Borrowdale volcanic groups) in late Ordovician (Sandbian) times; contemporaneous granite intrusions formed the core of the underlying Lake District batholith (Fig. 2).

Cessation of magmatism along the Avalonian margin in Katian times has been attributed to subduction of the Iapetus mid-ocean ridge (Pickering & Smith, 1995). Marine conditions became established across the eroded and thermally subsiding volcanic piles, and lasted until late Silurian times. During this period, 7 km of sedimentary rocks, now forming the Windermere Supergroup, were laid down across the Lake District in a foreland basin during the final stages in the closure of the Iapetus Ocean. However, the development of typical 'slate-belt' structures, such as folds and a regional cleavage, across the region appears to have climaxed during the Early Devonian, Acadian Orogeny, some 20 Ma after Iapetus had closed and probably as a result of subduction of the Rheic Ocean (Woodcock et al., 2007). Towards the end of this orogenic episode the Lake District batholith was enlarged further and a second batholith emplaced to the east beneath the North Pennines.

EYCOTT (EVG) AND BORROWDALE (BVG) VOLCANIC GROUPS.

The BVG comprises at least 6000 m of subaerially erupted basalt, andesite, dacite and rhyolite lavas, sills and pyroclastic rocks. There were two contrasting phases of volcanism (Millward, 2002). The initial one was dominated by andesite effusions that constructed a lava plateau of low-profile monogenetic volcanoes (Pettersen et al., 1992; Beddoe-Stephens et al., 1995). The 3200 m thick EVG closely resembles this first phase of the BVG. The ensuing second phase of the BVG was characterized by large-magnitude, caldera-forming, silicic pyroclastic eruptions, many of which produced high-grade ignimbrite, an unusual feature of destructive plate-margin volcanism (Branney & Kokelaar, 1994). At least eight depocentres operated during aggradation of the upper BVG (Millward, 2004). Most of the depocentres are aligned along an ENE trend through the central Lake District and were underpinned contemporaneously by components of the Lake District batholith.

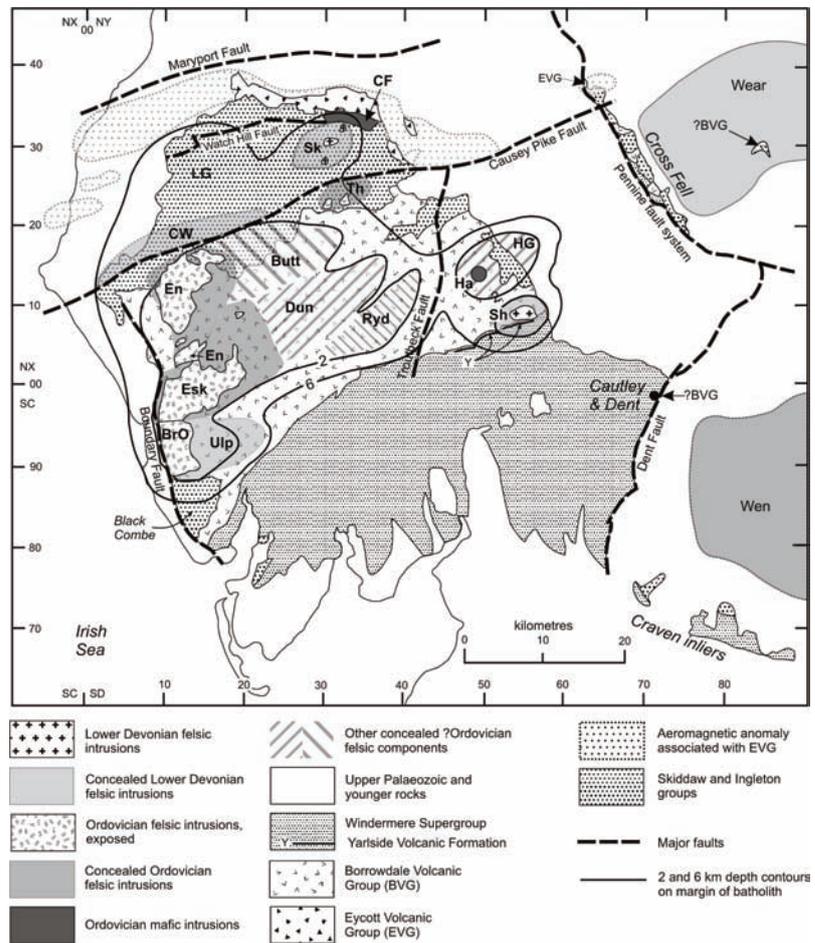


fig 2. Caledonian igneous rocks of the Lake District and adjacent areas. BrO Broad Oak Granodiorite Pluton; Butt Buttermere 'Granite'; CF Carrock Fell Centre; CW Crummock Water Granite; Dun Dunmail 'Granite'; En Ennerdale Granite Intrusion; Esk Eskdale Granite Pluton; Ha Haweswater Intrusions; HG Haweswater 'Granite'; LG Loweswater 'Granite'; Ryd Rydal 'Granite'; Sh Shap Granite Pluton; Sk Skiddaw Granite Pluton; Th Threlkeld Microgranite Intrusion; Ulp Ulpha 'Granite'; Wear Weardale Intrusion; Wen Wensleydale Intrusion. From Millward (2002).

Volcanotectonic collapse and caldera formation are fundamental mechanisms in preservation of this subaerial sequence. It has also been shown that these formed within two larger, intra-arc extensional basins (Millward, 2002). The complex history of the basin-bounding faults implies a significant role for re-activation of fractures in the Avalonian basement. Removal of Acadian strain shows the original width of the EVG and BVG graben to be 40 and 50 km respectively, figures that are not unlikely compared with the currently active Taupo Volcanic Zone of North Island, New Zealand, which is 300 km long and up to 60 km wide.

The volcanic rocks are typically abundantly porphyritic, mainly feldspar, clinopyroxene and orthopyroxene; almandine - pyrope garnet is present in

small amounts in some of the more acidic and peraluminous rocks of the BVG. The geochemical characteristics of the EVG rocks are transitional between medium-K, calc-alkaline and tholeiitic affinities, whilst the Borrowdale volcanic rocks are medium to high-K and calc-alkaline. The geochemical signatures are closely analogous to modern orogenic andesite suites emplaced through thick continental crust. Both groups can be modelled by POAM-type crystal fractionation of primitive melts, allied with crustal assimilation. The 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 crustal material. Localised highly systematic magmatic evolutionary trends or cycles have been identified (Beddoe-Stephens et al., 1995).

BATHOLITHS BENEATH NORTHERN ENGLAND.

Pioneering interpretations of the Bouguer gravity anomalies across the region in the 1960s linked surface granite exposures to two granitic batholiths underpinning northern England; the Lake District batholith underpinning the BVG, and further east, the North Pennine batholith (Fig. 2). Interpretation of field, gravity, seismic and radiometric data indicates that these have contrasting morphology and evolution. These data indicate that the composite Lake District batholith, with a concealed extent of more than 1500 km², is constructed from a core set of tabular plutons of late Ordovician age, with steep-sided, Early Devonian plutons around its margin. By contrast, the North Pennine batholith, 60 by 25 km in extent, comprises five juxtaposed, steep-sided plutons of Early Devonian age, only one of which, the Weardale Granite, has been proved by borings.

Within the Lake District batholith, exposed plutons having Sandbian radiometric ages, such as the Eskdale and Ennerdale granites, have laccolithic forms. Seismic reflection profiles across the western margin of these plutons exhibit zones of intense, sub-horizontal reflections intercalated with non-reflective ones; these are interpreted respectively as Skiddaw Group country rock and a set of stacked lenticular granitic sheets (Evans et al., 1994): i.e. a tabular sheet complex with a cedar-tree-like form. Country-rock xenoliths are very sparse within the exposed granites, favouring a model based on the sub-horizontal injection of tabular sheets approximately along the Skiddaw-Borrowdale Volcanic group contact, rather than stoping during forceful pluton emplacement (Millward, 2002).

By contrast, gravity modelling shows that the exposed Shap and Skiddaw granite plutons, with Early Devonian ages, have steep conical forms. A similar-shaped mass ('Ulpha Granite'; Fig. 2) concealed beneath the south-west of the Lake District is inferred to have a similar age and could be the source of the swarm of Early Devonian microgranite dykes, and of the tungsten, tin and bismuth mineralization that occur in adjacent areas. The concealed Crummock Water Granite in the north-western Lake District, is narrowly

elongate. Its form was inferred from the zone of intensely bleached Skiddaw Group mudstones and from interpretation of gravity data (Cooper et al., 1988).

ORDOVICIAN (SANDBIAN) PLUTONS.

Within the Lake District batholith, the Ennerdale Pluton is a relatively thin, tabular body of porphyritic granophyric granite, locally with dolerite, dioritic, and hybridized dioritic, granodioritic and melanocratic granitic rocks adjacent to its margin. To the south, the Eskdale Pluton consists of medium-grained muscovite granite, aphyric and megacrystic microgranite, and coarse to very coarse granite. The Broad Oak Pluton is typically medium-grained granodiorite, with hornblende and biotite. A quite separate intrusion, the Threlkeld Microgranite contains microphenocrysts of albite and orthoclase, and phenocrysts of corroded quartz and sporadic garnet.

The Threlkeld and Ennerdale granites, and the Broad Oak Granodiorite have geochemical similarities to the silicic volcanic rocks of the Borrowdale Volcanic Group which they underpin, and exhibit continental-margin volcanic-arc signatures. By contrast, many of the distinctive features of the Eskdale Pluton 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 all these granites were emplaced 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.

The Wensleydale Granite (Fig. 2) is composed of medium-grained granite. Though it has an Early Devonian Rb-Sr isochron age, the presence of cleavage, and its heat production value and geochemistry suggest that it belongs to the same suite as the Sandbian granites of the Lake District.

There are many swarms of typically small-volume mafic intrusions, showing varied geochemical characteristics. The largest of these is the Carrock Fell Centre which comprises mafic, mafic-felsic and felsic intrusions (Stephenson et al., 1999). The earliest intrusion, the Mosedale Gabbro Pluton, comprises

layered cumulate gabbros and forms the southern part of the complex. Cutting these rocks is the Carrock Pluton, consisting of a main mass of micrographic microgranite, intruded by a comagmatic, dyke-like body of microgabbro with a narrow zone of apatite-bearing iron-rich microdioritic rocks with Ca-rich pyroxene and amphibole.

LATE KATIAN VOLCANISM.

High-silica rhyolitic volcanic units were erupted into the shallow marine environment during late Katian time, 5–10 Ma after cessation of Borrowdale volcanism (Millward, 2002). Here, a major eruptive event is recorded by the Yarlsdale Volcanic Formation, which is dominated by a widespread felsite, and considered by many authors as lava flows, but also interpreted as a high-grade ignimbrite. Slightly later events eruptions emplaced the High Haume Tuff, Appletreeworth Volcanic Formations, Cautley Volcanic Member, and the Dam House Bridge Tuff: all are relatively small in volume.

EARLY DEVONIAN MAGMATISM.

The transtensional tectonic regime that existed at times during the early Devonian permitted emplacement of lamprophyre dykes throughout northern England (Soper & Woodcock, 2003). These magmas were large-fraction melts of depleted oceanic lithosphere that had been metasomatized by aqueous fluids derived from the dehydration of Iapetus oceanic crust during subduction and by a CO₂-rich phase from a deeper mantle source (Macdonald et al., 1985). Variable but small degrees of fractional crystallization were involved before final emplacement.

The Early Devonian Shap, Skiddaw and Weardale granite plutons in northern England are high heat-production granites; that is to say they contain relatively high abundances of radiothermal elements, including Rb, Th and U. They are distinct from the Ordovician granitoids in having relatively lower abundances of rare earth elements and Y (O'Brien et al., 1985). The Skiddaw Pluton is a biotite granite with quartz-white mica greisen, whereas the Shap Pluton comprises biotite monzogranite with alkali feldspar megacrysts. The Weardale Granite, is a two-mica granite with a shallow-dipping,

gneiss-like foliation. It is peraluminous in composition and is geochemically similar to the Skiddaw granite.

Farther north, the slightly later (Mid-Devonian) Cheviot Granite Pluton and its swarms of microgranite dykes, are comagmatic and coeval with the Cheviot Volcanic Formation. The latter rocks are the only record of volcanism known to have occurred at this time in the region, constituting a subaerial andesite lava field, at least 1500 m thick. The Cheviot Pluton comprises quartz monzonite, monzogranite and granophyric granite. The Cheviot volcanic rocks show similarities with other Old Red Sandstone volcanic rocks of the Midland Valley of Scotland, but there are also differences. For example, the Cheviot rocks are more potassic and, despite having strong enrichment in light rare-earth elements, the Sr content is low (Trewin & Thirlwall, 2002).

Despite the prevailing geotectonic environment at the end of Early Devonian times, a sedimentary protolith is unlikely as the source of the Early Devonian granites. Rather, the parental magmas were probably derived from a mafic source that contained residual garnet. These calc-alkaline granites are compositionally evolved rocks, yet show little evidence of an extended history of crystal fractionation. However, as with the Ordovician magmas before them, assimilation of Skiddaw Group material is implicated, particularly by the Sr, Pb and O isotope compositions.

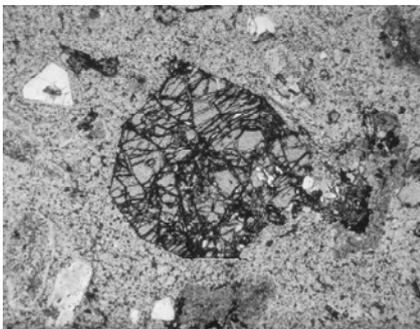


fig 3. Euhedral garnet phenocryst in the Cam Spout Dacite, English Lake District. Garnet is 2mm across

The mineral also occurs in microgranodiorite and dacite intrusions (Beddoe-Stephens and Mason, 1991), the Threlkeld Microgranite and in part of the Broad Oak Granodiorite. Fitton (1972) demonstrated unequivocally that BVG garnets are phenocrysts, that they

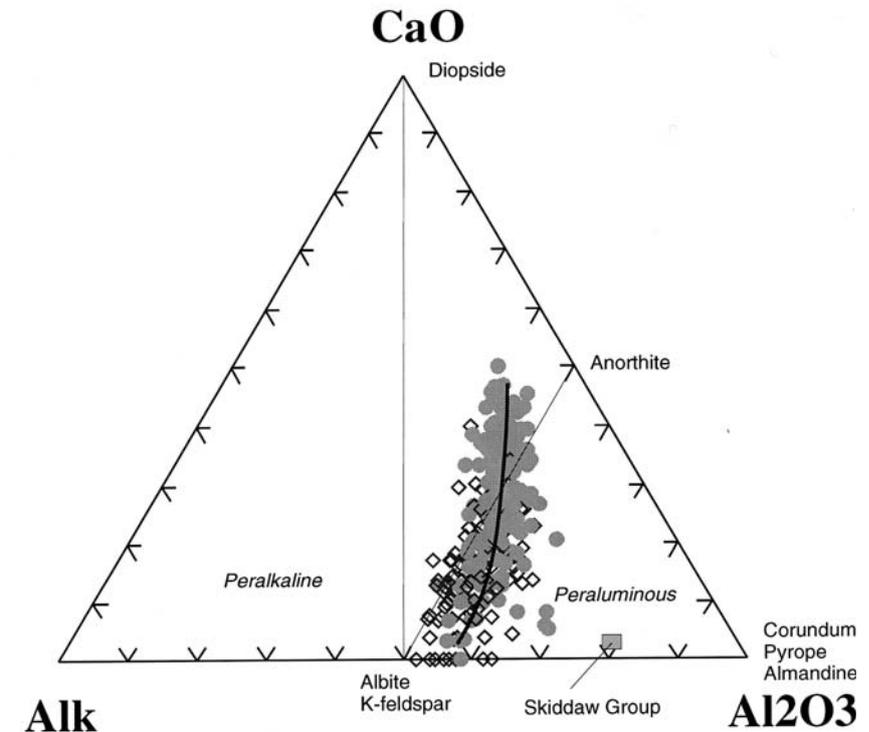


fig 4. Molar $\text{CaO-Al}_2\text{O}_3-(\text{Na}_2\text{O}+\text{K}_2\text{O})$ plot showing trend of the BVG from di-normative to c-normative. Skiddaw Group symbol is average composition.

occur in the peraluminous rocks (Fig. 4), and that compositions of the mineral and whole-rock are correlated. However, there is no evidence for garnet fractionation during evolution of the magmas (Fitton et al., 1982). Correlations between Nd, Sr and Pb isotope data, REE and Nb all show vectors towards average Skiddaw Group mudstone compositions, implying that the peraluminous nature of the more felsic rocks may be due to the assimilation of pelitic sediment. For the BVG, the most likely source of such material is the Skiddaw Group. Petrogenetic modelling by M F Thirlwall (pers. comm.) has suggested that between 10 and 40% mudstone has been incorporated in the variously contaminated magmas.

It has been argued that garnet may be stable at relatively low pressures of 5-7 kb (Fitton et al., 1982) or even about 3 kb (Beddoe-Stephens and Mason, 1991). However, the low-pressure stability of garnet within the compositional range seen in the volcanic rocks is poorly known. During the BGS research, a wealth of data on the spatial and stratigraphical distribution and on the petrology of garnet-bearing rocks

within the BVG has been accumulated and could provide the basis for isotopic and experimental petrological investigations designed to understand better the generation and evolution of magmas from which garnet crystallizes.

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