CARROCK FELL

D. Millward

OS Grid Reference: NY340320–NY360342

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).

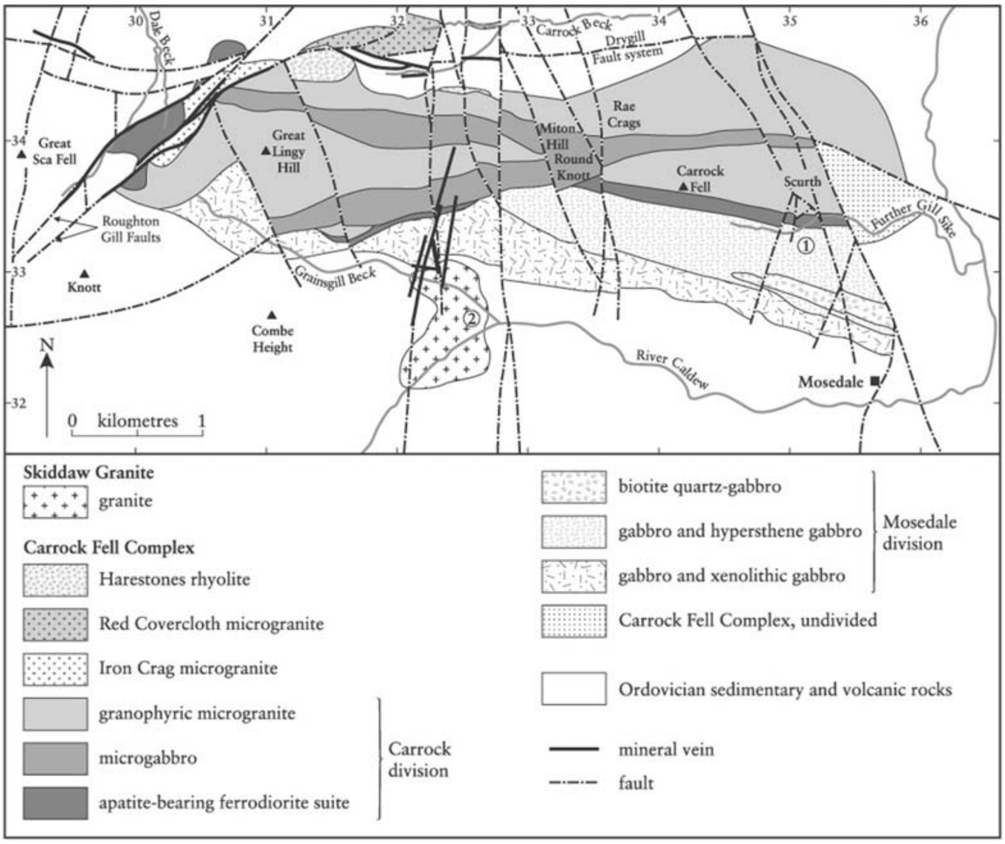

Figure 4.38: Map of the Carrock Fell Complex and the Skiddaw granite (after BGS 1:50 000 Sheet 23, 1997).

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 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.

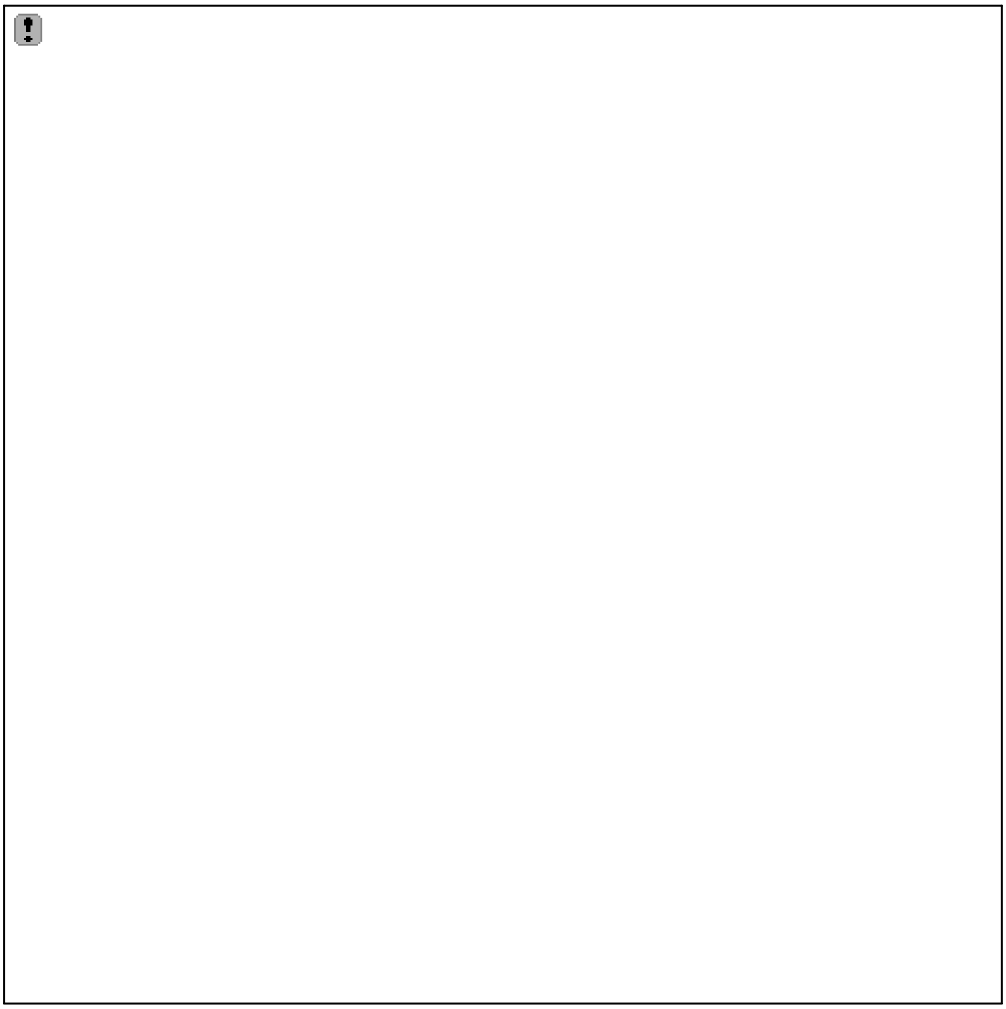

Figure 4.39: Panoramic view of the eastern end of Carrock Fell from the east side of Mosedale. The Caldew valley and the village of Mosedale are located far left. The stream just left of centre (arrowed) is Further Gill Syke and the amphitheatre-like landslip scar to the right of this, beneath the summit,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

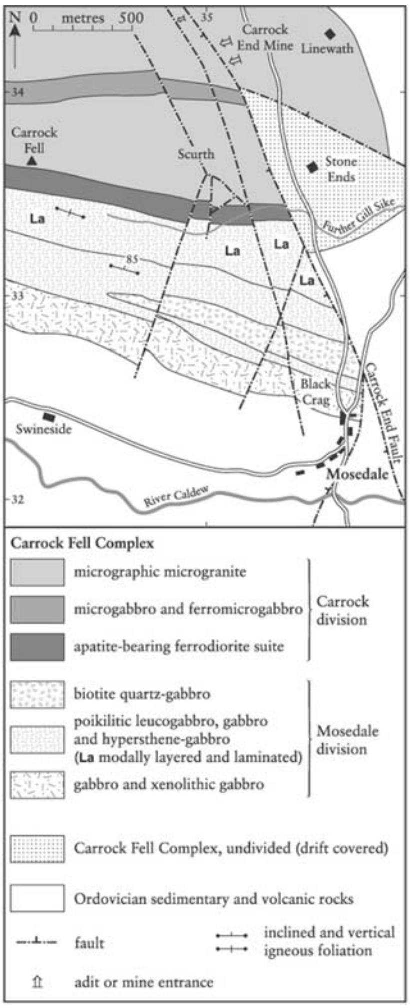

Figure 4.40: Map of the Carrock Fell GCR site.

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 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).

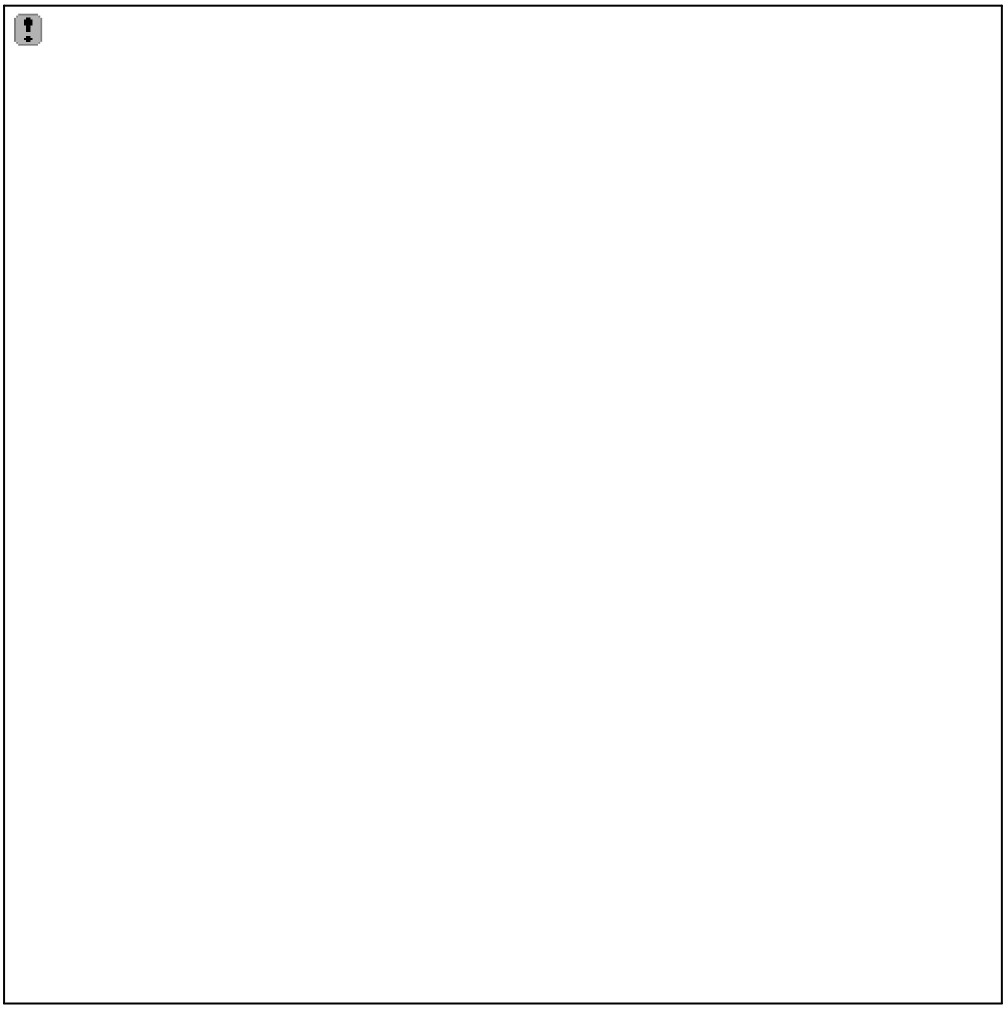

Figure 4.41: Modally layered gabbros from the Mosedale division. Alternation of leucocratic feldspathic and melanocratic mafic layers. (Photo: BGS no. A6743.)

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' ofEastwood *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 (Figures4.38, 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 ferromicrogranite 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 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 byPiper *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–microgranitic suite 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.

Reference list

Branney, M. J. and Soper, N. J. (1988) Ordovician volcano-tectonics in the English Lake District. *Journal of the Geological Society of London*, **145**, 367–76.
Briden, J. C. and Morris, W. A. (1973) Palaeomagnetic studies in the British Caledonides – III Igneous rocks of the Northern Lake District, England.*Journal of Geophysical Research*, **34**, 27–46.
Briden, J. C., Morris, W. A. and Piper, J. D. A. (1973) Palaeomagnetic studies in the British Caledonides – VI. Regional and global implications.*Geophysical Journal of the Royal Astronomical Society*, **34**, 107–34.
Brown, P. E., Miller, J. A. and Soper, N. J. (1964) Age of the principal intrusions of the Lake District. *Proceedings of the Yorkshire Geological Society*, **34**, 331–42.
Downie, C. and Soper, N. J. (1972) Age of the Eycott Volcanic Group and its conformable relationship to the Skiddaw Slates in the English Lake District.*Geological Magazine*, **109**, 259–68.
Eastwood, T., Hollingworth, S. E., Rose, W. C. C. and Trotter, F. M. (1968) Geology of the country around Cockermouth and Caldbeck. *Memoir of the Geological Survey of Great Britain*, Sheet 23 (England and Wales).
Faller, A. M. and Briden, J. C. (1978) Palaeomagnetism of Lake District Rocks. In*The Geology of the Lake District* (ed. F. Moseley), The Yorkshire Geological Society, Leeds, pp. 17–24.
Fitton, J. G. (1971) The petrogenesis of the calc-alkaline Borrowdale Volcanic Group, Northern England. Unpublished PhD thesis, University of Durham.
Green, J. F. N. (1917) The age of the chief intrusions of the Lake District.*Proceedings of the Geologists' Association*, **28**, 1–30.
Green, J. F. N. (1920) The geological structure of the Lake District.*Proceedings of the Geologists' Association*, **31**, 109–26.
Harker, A. (1894) Carrock Fell: a study in the variation of igneous rock-masses – Part I. The gabbro. *Quarterly Journal of the Geological Society of London*, **50**, 311–37.
Harker, A. (1895b) Carrock Fell: a study in the variation of igneous rock-masses – Part II. The Carrock Fell Granophyre. Part III. The Grainsgill Greisen.*Quarterly Journal of the Geological Society of London*, **51**, 125–48.
Harker, A. (1902) Notes on the igneous rocks of the English Lake District.*Proceedings of the*

Yorkshire Geological Society, **14**, 487–93.

Harland, W. B., Cox, A. V., Craig, L. E., Smith, A. G. and Smith, D. G. (1990)*A Geologic Time Scale 1989*, Cambridge University Press, Cambridge.

Harris, P. and Dagger, G. W. (1987) The intrusion of the Carrock Fell Gabbro Series (Cumbria) as a sub-horizontal tabular body. *Proceedings of the Yorkshire Geological Society*, **46**, 371–80.

Hollingworth, S. E. (1937) Carrock Fell and adjoining areas. Report of Field Meeting. *Proceedings of the Yorkshire Geological Society*, **23**, 208–18.

Hunter, R. H. (1980) The petrology and geochemistry of the Carrock Fell Gabbro-granophyre Complex, Cumbria. Unpublished PhD thesis, University of Durham.

Hunter, R. H. and Bowden, N. (1990) The Carrock Fell Igneous Complex. Itinerary 3. In*The Lake District* (ed. F. Moseley), The Geologists' Association, London, pp. 57–67.

Miller, J. A. (1961) The potassium-argon ages of the Skiddaw and Eskdale Granites. *Geophysical Journal*, **6,** 391–3.

Millward, D. and Molyneux, S. G. (1992) Field and biostratigraphic evidence for an unconformity at the base of the Eycott Volcanic Group in the English Lake District.*Geological Magazine*, **129**, 77–92.

Piper, J. D. A. (1997) Palaeomagnetism of igneous rocks of the Lake District (Caledonian) terrane, northern England: Palaeozoic motions and deformation at a leading edge of Avalonia. *Geological Journal*, **32**, 211–46.

Piper, J. D. A., Stephen, J. C. and Branney, M. J. (1997) Palaeomagnetism of the Borrowdale and Eycott volcanic groups, English Lake District: primary and secondary magnetization during a single late Ordovician polarity chron.*Geological Magazine*, **134**, 481–506.

Rundle, C. C. (1979) Ordovician intrusions in the English Lake District.*Journal of the Geological Society of London*, **136**, 29–38.

Skillen, I. E. (1973) The igneous complex of Carrock Fell.*Proceedings of the Cumberland Geological Society*, **3,** 363–86.

Ward, J. C. (1876) The geology of the northern part of the English Lake District.*Memoir of the Geological Survey of Great Britain*, Quarter Sheet 101SE (New Series Sheet 29, England and Wales).