Caledonian Igneous Rocks of Great Britain

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Chapter 5

Central England

INTRODUCTION

D. Millward

Occurrences of Caledonian intrusive and volcanic rocks in central England comprise a relatively small number of exposures within Lower Palaeozoic and Precambrian inliers, and provings from deep boreholes (Figure 5.1). Many of the localities and borehole sites are on the NE margin of the Midlands Microcraton, though some occur within it. For many years these igneous rocks were considered as Precambrian, along with those of Charnwood Forest. However, Le Bas (1972) proposed a Caledonian age for the igneous rocks at Warboys, Mountsorrel, South Leicestershire, Nuneaton and Dost Hill on the basis that they all could be inferred to intrude Lower Palaeozoic rocks. Recently, geochemical data and an increasing number of accurate U-Pb zircon dates have confirmed that igneous events occurred in this area during the late Proterozoic (at *c.* 615 Ma) and during the Ordovician (Noble *et al.*, 1993; Pharaoh *et al.*, 1993). The Precambrian occurrences are described in the *Precambrian of England and Wales* GCR volume.

Caledonian volcanic rocks in central England are almost entirely concealed, with the exception of the Barnt Green Volcanic Formation (Old *et al.*, 1991). The lower Silurian volcanic rocks of the Mendips and Tortworth area are described in Chapter 6 along with rocks of Skomer with which they are probably associated. Volcanic rocks are known to be widespread from well-documented borehole records (Pharaoh *et al.*, 1991, 1993; Figure 5.1). The volcanic rocks are calc-alkaline, arc-related and have been distinguished from the late Proterozoic rocks on their trace element abundances and isotopic compositions (Pharaoh *et al.*, 1991, 1993; Noble *et al.*, 1993). Though the compositional range includes basaltic andesite, andesite and rhyolite, felsic tuff predominates; no dacite is recorded. An Ordovician age has been determined for felsic tuff from the North Creake Borehole (449 ± 13 Ma, U-Pb zircon, Noble *et al.*, 1993).

The Ordovician plutons are also calc-alkaline (Le Bas, 1972, 1982b) and one group is aligned broadly along a NW–SE belt of crust with strongly positive aeromagnetic anomalies (Allsop, 1987; Pharaoh *et al.,* 1991, 1993). The recent summary of the occurrences and geochemistry of the igneous rocks of Central England by Pharaoh *et al.* (1993) has shown that the largely Triassic cover rocks conceal a substantial magmatic province of late Ordovician age. Pharaoh *et al.* (1993) speculated that the magnetic anomaly belt may mark the magmatic core of a continental calc-alkaline volcanic and plutonic province. Le Bas (1972, 1982b) and Pharaoh *et al.* (1991) have suggested that this belt of arc-related rocks extends eastwards into Belgium. The development of the putative arc at the eastern margin of Avalonia may have been the product of the subduction of oceanic lithosphere during closure of the Tornquist Sea (Pharaoh *et al.*, 1993). The lithologies, geochemistry and timing of Caledonian magmatism have considerable similarities with the Lake District magmatic province, but the tectonic relationships are yet to be understood.

Plutonic rocks

Three groups of plutonic rocks are recognized (Figure 5.1). The first of these, known as the 'South Leicestershire diorites', crops out on the margin of the Midlands Microcraton SW of Leicester. The second group is associated with a belt of positive aeromagnetic anomalies up to 10 km wide and extending about 125 km from Hathern, near Derby to St Ives in Huntingdonshire (Allsop, 1987); examples of these plutonic rocks include the exposed Mountsorrel complex and occurrences in the Rempstone, Kirby Lane and Warboys 1 boreholes. The xenolithic granodiorite from Rempstone is petrographically similar to Mountsorrel. Farther NE, in south Lincolnshire, cleaved and altered granophyric microgranite in the Claxby borehole has been dated at 457 ± 20 Ma (Noble *et al.*, 1993). The microgranite is geochemically similar to Ordovician intrusions of the Lake District (Pharoah *et al.*, 1997). While it is part of a third group of silicic plutons interpreted from geophysical anomalies in the area around the Wash (Busby *et al.*, 1993), it is not considered to be a major component of that batholith (Pharoah *et al.*, 1997).

The *South Leicestershire diorites* comprise diorite, tonalite and microtonalite and are, or were formerly, exposed at Stoney Stanton (SP 490 950), Croft (SP 510 967), Coal Pit Lane Quarry (SP 542 992), Enderby (SP 542 992), Red Hill Quarry, Narborough (SP 532 975) and Narborough Quarry (SP 525 975); the Countesthorpe borehole also penetrated these rocks

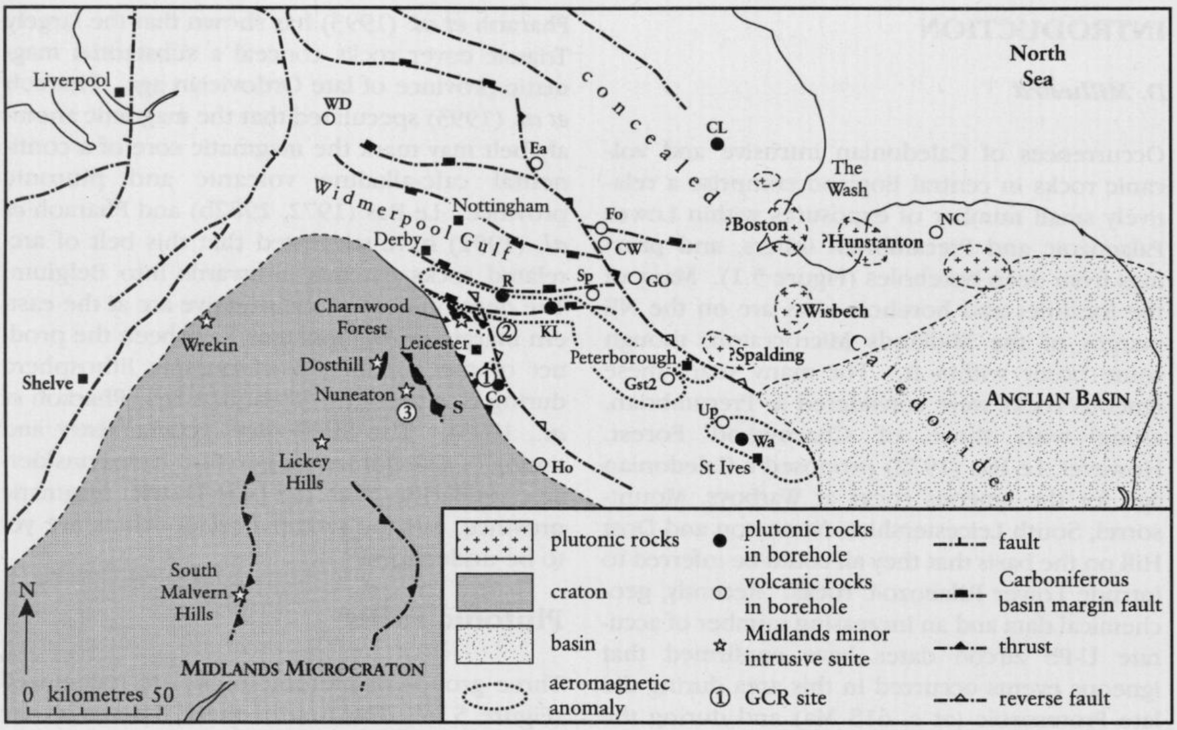

Figure 5.1 Map of central England showing locations of the occurrences of Caledonian igneous rocks and the GCR sites (after Pharaoh *et al*., 1993). GCR sites: 1, Croft Hill; 2, Buddon Hill (Mountsorrel); 3, Griff Hollow. Occurrences of plutonic rocks: Cl, Claxby; Co, Countesthorpe; KL, Kirby Lane; R, Rempstone; S, South Leicestershire diorites; Wa, Warboys 1. Occurrences of volcanic rocks: CW, Coxs Walk; EA, Eakring 146; Fo, Foston; GO, Great Osgrove Wood 1; Gst2, Gas Stamford 2; Ho, Hollowel; NC, North Creake 1; Sp, Sproxton; Up, Upwood 1; WD, Woo Dale 1.

(Figure 5.1). The diorite is quartz bearing and contains hornblende and sparse augite. The tonalite is described in detail from the Croft Hill GCR site. Le Bas (1972) considered that these occurrences form a composite pluton about 14 km wide, intruding the Cambrian Stockingford Shale Group. The age of the intrusions is taken at 449 ± 18 Ma (U-Pb; Pidgeon and Aftalion, 1978; recalculated by Noble *et al*., 1993).

The *Mountsorrel complex*, about 10 km north of Leicester, comprises gabbro, diorite and granodiorite. The gabbro is exposed only on a small island in Swithland Reservoir and is composed of labradorite and ophitic brown hornblende enclosing relict augite; pseudomorphs after olivine may be present. The diorite is similar to the South Leicestershire suite (above) but contains more biotite. However, the most extensive rock type is a biotite granodiorite well illustrated by the Buddon Hill GCR site near Mountsorrel. The age of the complex is taken at 463 ± 32 Ma (U-Pb; Pidgeon and Aftalion, 1978; recalculated by Noble *et al*., 1993).

Midlands Minor Intrusive Suite

The Cambrian and Tremadoc rocks within, and at the margin of, the Midlands Microcraton are intruded by lamprophyre (spessartite) and diorite dykes and sills. The field occurrence, petrography and geochemistry are detailed in Carney *et al*. (1992), Thorpe *et al*. (1993a) and Bridge *et al*. (1998). Exposures of these rocks are in quarries close to Nuneaton, near the Wrekin in Shropshire and in the Malvern Hills (Figure 5.1). The suite is typified by the 50 m-thick composite sill of spessartite, hornblende diorite and hornblende meladiorite described from the Griff Hollow GCR site; that sill has a U-Pb emplacement age of 442 ± 3 Ma (Noble *et al*., 1993). In the Tremadoc Shineton Shales of the Wrekin area a single lenticular mass is exposed in an old quarry (SJ 645 087). The mineralogy of this occurrence differs from those at Nuneaton in containing no magmatic amphibole and up to 20% clinopyroxene. The presence of olivine and absence of quartz distinguishes this group from the other Caledonian igneous rocks of central England.

A small, faulted inlier at the southern end of the Lickey Hills, south of Birmingham (Figure 5.1) comprises water-laid crystal and crystal-lithic tuffs together with other volcaniclastic sedimentary rocks of the Tremadoc Barnt Green Volcanic Formation, intruded by aphyric microdiorite intrusions (Old *et al.*, 1991). Geochemical comparisons led Carney *et al.* (1992) to suggest that these rocks may belong to an early, extrusive phase related to the Midlands Minor Intrusive Suite, thus implying that this magma type was available over a substantial time-span.

CROFT HILL (SP 510 967)

J. N. Carney and T. C. Pharaoh

Introduction

The Croft Hill site exhibits coarse-grained plutonic rocks as small crags and pavements on the summit and flanks of the 123 m-high Croft Hill, and in the face of Croft Quarry, which is excavated into the SE side of the hill (Figure 5.2). These rocks have been studied petrographically over a long period of time; they were originally described as syenite (Hill and Bonney, 1878) before Whitehead (in Eastwood *et al.*, 1923) suggested that, as no alkali feldspar is present, they should be classified as quartz-diorite or tonalite. The Croft pluton is now assigned to an assemblage of calc-alkaline intrusive rocks which, because of their geographical distribution, are collectively termed the 'South Leicestershire diorites' (Le Bas, 1968). These bodies are mostly hidden beneath Triassic strata, but have magnetic properties that enable them to be traced at depth as a series of small batholiths. The Croft Hill exposure is part of a composite pluton about 14 km wide, which is linked at depth with similar plutonic rocks cropping out around Stoney Stanton to the west and Enderby to the east (Allsop and Arthur, 1983).

The significance of these rocks to the geology of central England is, in part, their age. A U-Pb date of 449 ± 18 Ma was obtained on zircon from the tonalitic rocks exposed at Enderby NE of Croft Hill (Pidgeon and Aftalion, 1978; recalculated by Noble *et al.*, 1993), and is the currently accepted emplacement age of the South Leicestershire diorites. The plutons therefore belong to an Ordovician (late Caradoc) intrusive event, contemporaneous with the subduction-related magmatism of central Wales and the Lake District (Pharaoh *et al.*, 1993). Their presence confirms that an extension of the Caledonian orogenic belt lies beneath much of central and eastern England (Le Bas, 1972; Pharaoh *et al.*, 1987).

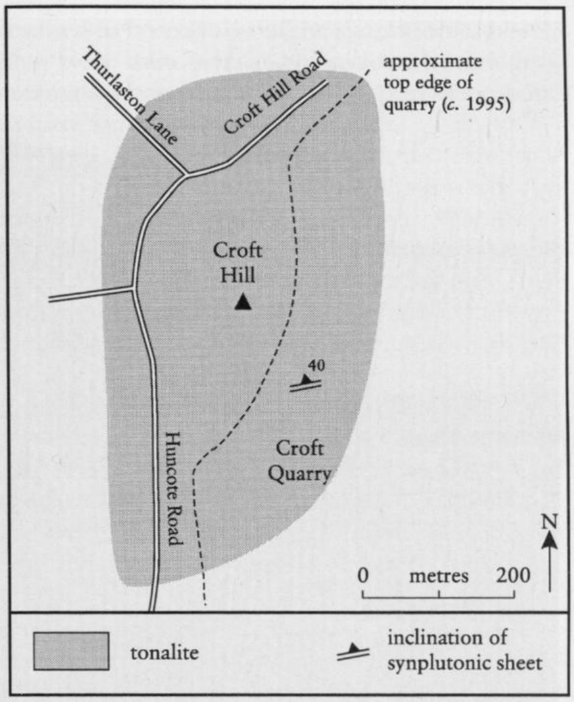

Figure 5.2 Map of the Croft Hill GCR site.

The Croft Hill site with its adjacent quarry offers extensive exposures demonstrating the petrology and internal intrusive history of a typical South Leicestershire pluton. It is also the location for an analcime-molybdenite style of mineralization, which is here more intensively developed than elsewhere in the pluton.

Description

On the NW flank of Croft Hill small crags of inequigranular tonalite display abundant small white plagioclase phenocrysts set in a crumbly yellow or brown, medium-grained weathered base. At the summit, pavements of the same

Figure 5.3 View of Croft Hill, showing the NW face of Croft Quarry. To the left of the picture, the dark-grey parallel lineaments dipping from top left to bottom right represent a swarm of synplutonic intrusive sheets. (Photo: J. N. Carney.)

rock type are transected by an orthogonal fracture system, the principal trends of which are 360°, 260° and 240°.

Below the summit of Croft Hill, in the NW face of Croft Quarry (Figure 5.3), is exposed massive, pale-grey, inequigranular medium- to coarse-grained tonalite. This is characterized by common large crystals of white euhedral plagioclase, up to 6 mm long, within a pink, medium-grained quartzo-feldspathic base studded with black oxide granules. The tonalite has a hypidiomorphic, inequigranular texture, with abundant euhedral plagioclase crystals, some with labradorite cores and rimmed by grainy, inclusion-filled albite. Surrounding these crystals are aggregates of smaller, inclusion-filled sodic plagioclase crystals which are in part idiomorphic and in part form an interlocking granular intergrowth with quartz. Clinopyroxene forms sporadic euhedra and aggregates largely altered to chloritic minerals; small tatters of biotite are similarly altered. Plagioclase is pervasively replaced by patches and veinlets of albite. Pumpellyite occurs interstitially, and Webb and Brown (1989) noted radial prehnite infilling cavities and zeolites occupying veins.

A major feature of the intrusion occurs lower down in the same quarry face, where several sheets of darker-grey tonalite, 1 m to 3 m wide, extend up the face for tens of metres and form a well-spaced 'swarm' dipping at about 40° to the NNW. The contact between these sheets and the host tonalite is sharp and irregular; slivers of the sheets are incorporated as xenoliths in the host. Neither the sheet nor the host is chilled, but the latter has intimately permeated the sheets as diffusely margined stringers of pale-grey tonalite which divide the sheet into rectangular to ovoid segments. The grey tonalite is mineralogically similar to the host, but is medium grained and non-porphyritic. Elsewhere in the quarry augite-bearing microdiorite xenoliths are common in the tonalite (Le Bas, 1968).

Prominent joint systems seen in the quarry below Croft Hill comprise a master set dipping 25° NNE and a subordinate set at right angles to this. In the SW quarry face, a prominent discontinuity outlines what appears to be a gentle dome-shaped structure, dividing intrusive rocks with different joint orientations. The nature of this structure cannot be determined as this part of the quarry is inaccessible.

The mineralization in Croft Quarry principally comprises the replacement of feldspar minerals by albite and analcime, producing the characteristic pink colour of the tonalites (King, 1968). The final stages of this alteration is known by local miners as 'rammel', which occurs in layers up to 12 m thick of completely disaggregated rock, commonly with cavities lined by crystals of analcime, calcite and quartz; prehnite, datolite, laumontite and dolomite are accessory minerals of this assemblage. The occurrence of minor amounts of molybdenite in this association is unusual because it normally belongs to a high-temperature environment, whereas analcime characterizes mesothermal and lower temperature environments (King, 1968).

Triassic strata mantle the southern part of the Croft tonalite and the highly irregular contact is well exposed just outside the limits of the site (Le Bas, 1993).

Interpretation

The rocks of Croft Hill constitute one of the few exposures of Caledonian igneous 'basement' in central England. Research during the 20th century has emphasized the unusual mode of occurrence of these rocks, as a pinnacle or inselberg buried beneath Triassic strata (Bosworth, 1912). Recent geophysical investigations have demonstrated that a much larger parent body is present at depth (Allsop and Arthur, 1983). Thus, the composition and variation seen within the Croft intrusion should be considered together with the very similar lithologies exposed at Stoney Stanton and Enderby, and encountered in the Countesthorpe borehole (Le Bas, 1972).

The Croft tonalitic intrusion is evidently part of a small, zoned batholith, with diorites to the west and microtonalite to the east (Le Bas, 1972). The Croft Quarry exposures suggest that even on a small scale, the batholith may have multiple phases of intrusion. The first phase comprised pale-grey inequigranular coarse-grained tonalite, which constitutes most of the northern face below Croft Hill. Parallel sheets of a darker-grey and more evenly grained tonalite were then emplaced into the main body, probably as a series of synplutonic intrusions because neither these sheets nor the host show chilling. Subsequent minor remobilization of the host resulted in brecciation of the synplutonic sheets. They were then extensively invaded by stringers emanating from the host, and in part stoped-out to form xenoliths within the latter.

The South Leicestershire diorites exhibit a strongly calc-alkaline geochemical signature (Le Bas, 1972; Webb and Brown, 1989). Pharaoh *et al.* (1993) noted that the Croft rocks show moderate enrichments of large-ion lithophile elements (K, Rb and Ba), Th and Ce, and relative depletion of Nb and Ta, which are patterns typical of calc-alkaline magmas arising within a volcanic arc founded on continental crust. The subduction zone above which the magmas were generated may have been situated to the east of central England in late Ordovician times, its activity related to the phase of plate convergence that closed the Tornquist Sea (Noble *et al.*, 1993).

The widespread extent of albite and analcime replacement suggests pervasive deuteric alteration of the Croft rocks, a process possibly enhanced by the relatively complex emplacement history of the pluton evidenced by its zonation on a regional scale. The occurrence of molybdenite in association with these secondary minerals is unusual and not understood fully.

Conclusions

The tonalites of the Croft Hill GCR site belong to the suite of late Ordovician intrusions known as the 'South Leicestershire diorites'. They represent one of the few exposures of the central zone of a small batholith, the larger part of which lies hidden beneath Triassic rocks. On a regional scale, the Croft body shows compositional zoning, indicative of a complex intrusive history. This is demonstrated at the smaller scale in Croft Quarry, where several parallel sheets of equigranular tonalite cut the host inequigranular coarse-grained tonalite, but were then brecciated and invaded during subsequent mobilization of the latter. Pervasive post-emplacement alteration of the tonalites involved the conversion of feldspar to albite, analcime and other zeolites, and was accompanied by minor molybdenite mineralization. The age and calc-alkaline geochemistry of the Croft rocks show that they were generated within a SE extension of the Caledonian magmatic belt and were contemporaneous with the volcanic and intrusive rocks of central Wales and the Lake District.

BUDDON HILL (SK 562 154)

J. N. Carney and T. C. Pharaoh

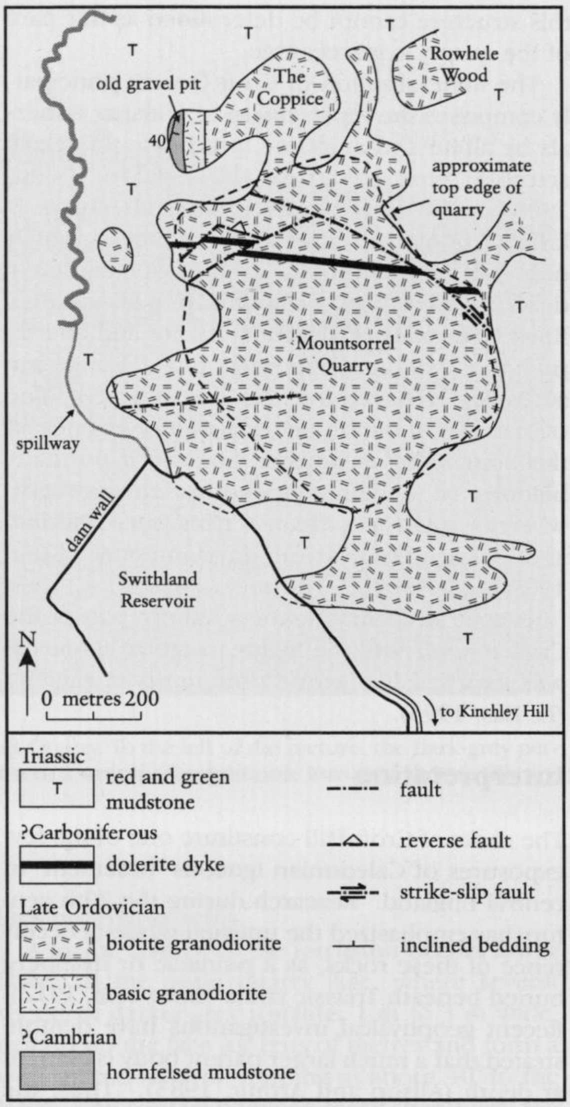

Figure 5.4 Map of the Buddon Hill GCR site, based in part on BGS 1:10 560 scale mapping.

Introduction

The Buddon Hill GCR site comprises isolated rocky knolls in woodland to the north and east of the Swithland Reservoir and includes most of the central and western parts of the Mountsorrel roadstone quarry (Figure 5.4). Features that underline the importance of the site to studies of central England Caledonian magmatism include: the considerable extent of exposure, the variety of igneous rock types and contact relationships that they portray, and the more silicic nature of the Mountsorrel complex (Le Bas, 1968, 1972) compared with the otherwise compositionally similar Croft pluton (see the Croft Hill GCR site report). Geophysical studies indicate that the complex extends beneath younger cover rocks to the village of Thrussington, about 8 km to the east (Hallimond, 1930; McLintock and Phemister, 1931). Borehole provings also suggest that comparable granodioritic rocks are regionally developed (Pharaoh *et al.*, 1993).

Early workers thought the Mountsorrel rocks were part of the Precambrian Charnwood Forest massif (e.g. Hill and Bonney, 1878). Lowe (1926) drew attention to the predominantly granodioritic composition, whereas Jones (1927) suggested, on the basis of jointing, that they represent an intrusion of 'post-Charnian' age. Meanwhile, Watts (prior to publication in 1947) had concluded that the rocks have petrological affinities with the igneous 'Caledonian group' of the Lake District. This view was seemingly confirmed by Meneisy and Miller (1963), who obtained a K-Ar age of 379 ± 17 Ma on biotite from a diorite from Brazil Wood, to the SW of Buddon Hill. However, the emplacement age is constrained better by the U-Pb determination of 463 ± 32 Ma (early Caradoc) on zircon from the Mountsorrel complex (Pidgeon and Aftalion, 1978; recalculated by Noble *et al.*, 1993). The Caledonian age of the Mountsorrel rocks is in keeping with their strongly calc-alkaline geochemistry, comparable to some intrusions of the Brabant Massif of Belgium and the English Lake District (Le Bas, 1972; Pharaoh *et al.*, 1993). These rocks therefore provide evidence for Ordovician calc-alkaline magmatism in eastern England, probably associated with subduction of oceanic lithosphere from an eastern Tornquist branch of the Iapetus Ocean (Pharaoh *et al.*, 1993).

The site contains one of the few exposures of contact relationships between these plutonic rocks and cleaved, hornfelsed mudstone. Le Bas (1968) noted that the metasedimentary country rocks are more iron-rich, and less siliceous, than the Swithland Slates of the Precambrian Charnian Supergroup, and may instead correlate with Cambrian strata similar to the Stockingford Shale Group exposed around Nuneaton (e.g. Taylor and Rushton, 1971). However, there is no direct evidence to support either hypothesis.

A basic dyke, thought to belong to the late Carboniferous alkaline cycle of magmatism (Le Bas, 1968), and the highly irregular unconformable base of the Triassic strata are displayed within the Mountsorrel Quarry.

Description

The slopes above the NE shore of Swithland Reservoir (5607 1461) expose pink-weathered, inequigranular coarse-grained biotite granodiorite which represents the voluminous, main phase of the Mountsorrel complex. Laths and euhedral plates of plagioclase (about 60%) are surrounded by hypidiomorphic-granular aggregates of albite, inclusion-filled perthitic alkali feldspar and clear quartz; the mafic minerals are mainly brown biotite and yellow to green hornblende. The granodiorite encloses sporadic pink to grey, rounded xenoliths of equigranular diorite averaging 50 mm across. It is cut by sheets of fine- to medium-grained aplitic microgranite between 10 mm and 0.15 m wide: similar late sheets are visible in exposures northwards along this slope, up to the wall of the dam.

North-east of the dam the granodiorite is coarser grained and more inequigranular, a texture that is well displayed at the summit of the prominent knoll overlooking the spillway (5575 1501). This exposure exhibits two phases of aplitic intrusion (Figure 5.5); the first comprises a vertical sheet 0.45 m thick striking NNE and the second, a cross-cutting sheet dipping 40° to the NE. At the base of this knoll, to the west, in a small quarry is a pale-grey, mafic-rich 'basic granodiorite' (Le Bas, 1968), suggesting proximity to the margin of the pluton.

Contact relationships between granodiorite and country rock were described by Watts (1947) at the 'Old Gravel Pit' (5582 1555), about 670 m NNE of the dam. At this locality, now much overgrown, purple, micaceous, hornfelsed mudstone is traversed by sinuous veinlets of pink granodiorite, and by sheets several centimetres wide of pink to grey, medium-grained equigranular 'basic granodiorite'. According to Watts (1947), the hornfels contains garnet and cordierite.

Granodiorite forming the eastern part of Mountsorrel Quarry appears relatively devoid of aplitic microgranite sheets and contains only sporadic, small rounded xenoliths of dark-grey medium-grained diorite. Farther west, aplitic sheets and xenoliths are more common, and two phases of intrusion can be recognized, the second accompanied by marginal chilling of the sheets. The fresh granodiorite is a grey, inequigranular, coarse-grained rock speckled with biotite. High-temperature alteration, which has caused reddening of feldspars and replacement of the mafic minerals, occurs in association with wide zones of closely spaced E–W orientated joints, the surfaces of which show slickenfibre development. Within the altered zones, King (1968) determined a lower temperature mineral assemblage of dolomite, epidote, chlorite, quartz, chalcopyrite and pyrite together with minor amounts of galena, calcite, haematite and baryte. The style of this mineralization is comparable to that seen at Shap in the Lake District (see the Shap Fell Crags GCR site report, Chapter 4).

A sub-vertical dolerite dyke 2–3 m wide crosses the quarry, following an approximately E–W course related to the trend of the principal fracture systems in the granodiorite. It is dark-green, medium grained and reminiscent in appearance to Carboniferous minor intrusions found in the region; the precise age is uncertain. In the eastern quarry face the dyke shows an apparent dextral offset along the NW fault which crosses the quarry. The western face exhibits an offset along an arcuate reverse fault dipping steeply to the NE. A second mineralizing event has filled joints parallel to the dolerite and consists of cavernous veinlets with dolomite, calcite, bitumen, a clay mineral and pyrite. A hydrothermal origin for the bitumen was suggested by Sylvester-Bradley and King (1963), and Ponnamperuma and Pering (1966).

In the eastern face of the quarry an excellent example of a Triassic valley eroded into the granodiorite is preserved. The lower part of the valley is occupied by a breccia of granodiorite fragments, overlain by red and green parallel-bedded mudstone and siltstone.

Interpretation

The site exposes a variety of plutonic rocks near to the western margin of the Mountsorrel complex. Close to the contact, the exposures show that the plutonic rocks have veined the country rock, with the growth of garnet and cordierite in hornfelsed mudstone of possible Cambrian age.

The earliest phase of the Mountsorrel complex may be the dioritic xenoliths. These are

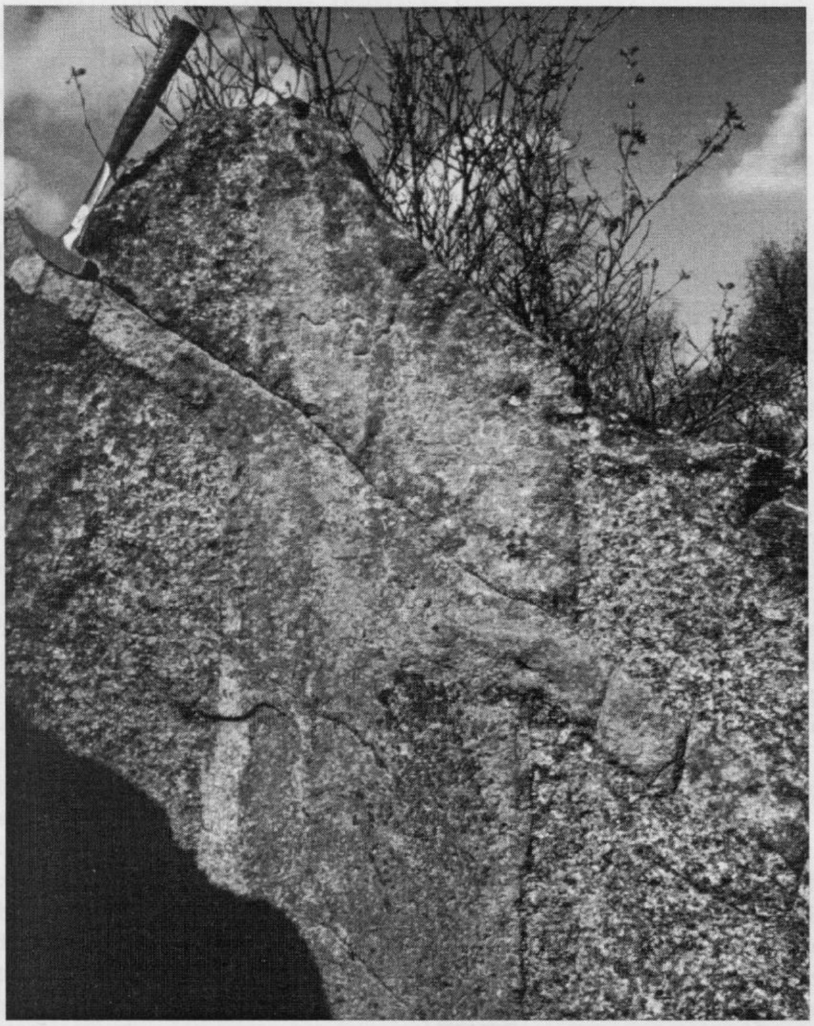

Figure 5.5 Exposure of granodiorite at Buddon Hill showing two phases of aplite intrusion. (Photo: T. C. Pharaoh.)

possibly cognate inclusions derived from a basic precursor that was disrupted during intrusion of the main-phase biotite granodiorite, though other explanations are possible. The persistence of basic granodiorite close to the western contact of the pluton was attributed by Taylor (1934) to reaction between granodiorite and pre-existing diorite. A different interpretation was proposed by Le Bas (1968), who suggested that at Kinchley Hill, 450 m south of the site, the intrusive relationships indicate that granodiorite and diorite were contemporaneous, facilitating processes of hybridization that basified the former and acidified the latter. The main-phase biotite granodiorite was subsequently veined by at least two generations of aplitic microgranite sheets. These were interpreted by Taylor (1934) to be the relatives of a sodic 'aplogranite magma' which, after hybridizing at depth with gabbro or diorite, had given rise to the main body of granodiorite. Alternatively, the aplitic rocks could be differentiates of the granodiorite injected back into the partially cooled pluton. This late magmatic environment favoured the molybdenite mineralization seen in association with aplitic and pegmatitic rocks in other parts of the Mountsorrel complex (King, 1959, 1968).

The locally extensive low-temperature alteration of the Mountsorrel body was attributed to deuteric mineralization by King (1968), though it may also be related to the formation of E–W joint systems, implying an underlying tectonic control.

Major element geochemical data discussed by Le Bas (1972) demonstrate the calc-alkaline magmatic lineage of the Mountsorrel complex.

Studies of trace elements show enrichment of the large ion lithophile elements Th and Ce with respect to high field-strength elements such as Nb, Zr and Y, further confirming the calc-alkaline arc affinities of the complex and its similarity to the South Leicestershire diorites (Pharaoh *et al.*, 1993). All of these rocks are therefore interpreted as products of late Ordovician subduction-related magmatism.

The final magmatic event, uniquely exposed in Mountsorrel Quarry, was the emplacement of the E–W-trending dolerite dyke, possibly in Carboniferous times. Hydrothermal fluid circulation caused the low-grade mineralization that is spatially associated with the dyke. The combination of dextral strike-slip and reverse faulting that affected the dyke suggests a significant component of Variscan transpression which may have contributed to the structural complexity of the Mountsorrel pluton.

Conclusions

The Buddon Hill GCR site represents the only extensive exposures of the Mountsorrel complex of late Ordovician calc-alkaline plutonic rocks. It clearly demonstrates a sequence of intrusion commencing with diorite and biotite granodiorite and closing with aplitic microgranite. Alteration of these phases by water-rich fluids derived from the magmas, to assemblages that include albite may have been, at least in part, structurally controlled. One of the main features of the site is an exposure of the western contact of the complex. This shows granodiorite veining fine-grained metasedimentary rocks which have been converted to a garnet-cordierite hornfels. A dolerite dyke crossing the Mountsorrel Quarry may be Carboniferous in age; it has acted as a passive marker, illustrating a possible Variscan phase of deformation. The highly irregular unconformity at the base of the Triassic strata is preserved around the margin of Mountsorrel Quarry.

GRIFF HOLLOW (SP 361 895)

J. N. Carney and T. C. Pharaoh

Introduction

The Griff Hollow GCR site is situated within the Nuneaton inlier of pre-Devonian rocks (Bridge *et al.*, 1998). It is largely occupied by the Griff No. 4 aggregate quarry (Figure 5.6). The site has been selected because it exposes the type example of a composite hornblende diorite sill, one of a swarm of concordant bodies collectively termed the Midlands Minor Intrusive Suite (Carney *et al.*, 1992). The sill, about 50 m thick, is intruded into Upper Cambrian mudstone belonging to the Outwoods Shale Formation of the Stockingford Shale Group (Taylor and Rushton, 1971). Its emplacement age has been constrained at 442 ± 3 Ma by a U-Pb determination on baddeleyite from a pegmatitic segregation (Noble *et al.*, 1993). This late Ordovician (earliest Ashgill) age is similar to that determined for the South Leicestershire diorites exposed farther east.

The Midlands Minor Intrusive Suite differs from the South Leicestershire diorites in a number of important respects. The Griff Hollow composite sill is intimately associated with narrow sheets of fine-grained lamprophyre, a rock that is not associated with the South Leicestershire diorites. Petrographical studies further support the assertion made by Allport (1879) that the Nuneaton sills contain olivine and are thus devoid of essential quartz. Other significant geochemical differences exist between the two Ordovician intrusive suites (Bridge *et al.*, 1998). Therefore the site is important in comparative studies aimed at resolving the causes of both regional and local petrological variations within the late Ordovician (Caledonian) magmatic rocks of central England.

The NW corner of the quarry contains an exposure of the unconformity between the sill and overlying Coal Measures sandstones, providing field evidence for the pre-Carboniferous (Westphalian) age of the Midlands Minor Intrusive Suite.

Description

Igneous layering within the Griff Hollow sill dips at about 20° to the SW, parallel to the base of the sill and concordant with bedding in the Stockingford Shale Group. The host strata contain slumped bedding, but were evidently well consolidated at the time of intrusion; they are not spotted, but are flinty and hard for several centimetres from the contact.

The sole of the intrusion consists of a 20 cm-thick chilled zone of fine-grained spessartite

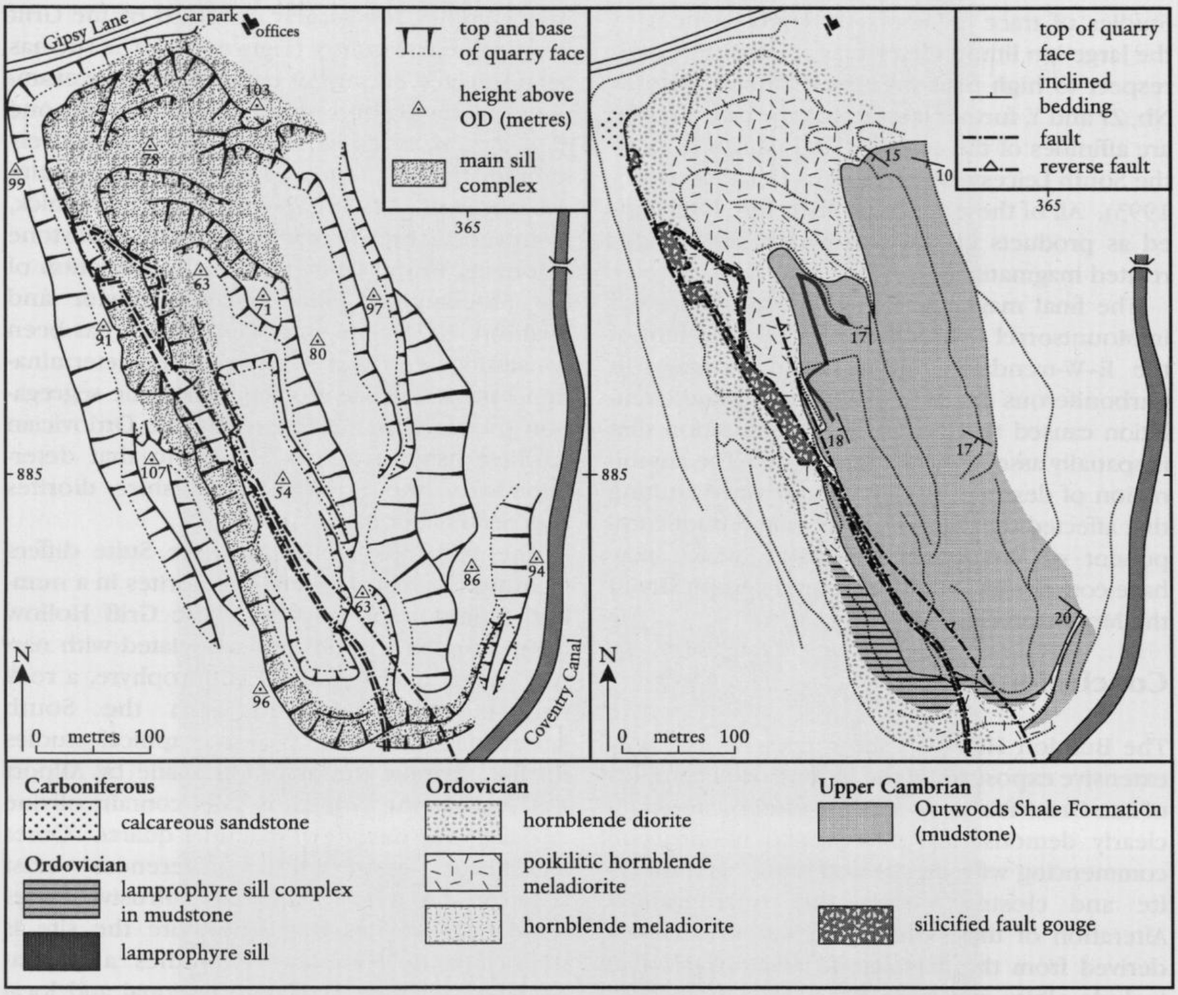

Figure 5.6 Map of the Griff Hollow GCR site (modified from Bridge *et al.*, 1998). Positions of quarry faces in 1990 are shown.

lamprophyre. Abundant flow-aligned plagioclase laths are accompanied by a few per cent of small plagioclase and chloritized mafic phenocrysts. The base is much altered with interstitial chlorite and carbonate, which also fill small vugs. The lowest part of the sill in the SE of the quarry is replaced by a sheeted complex consisting of *c.* 1 m-wide lamprophyre sills interfingered with the host mudstone. These sills are texturally and mineralogically similar to the basal facies of the main part of the composite sill and to discrete lamprophyre sheets cutting the rest of the Griff Hollow intrusion.

Overlying the basal lamprophyre are 4–5 m of dark-grey, medium-grained hornblende meladiorite characterized by a thickly developed planar foliation, parallel to the basal contact of the sill, and consisting of dark-grey diorite interlayered with a paler-grey, more feldspathic variety. The meladiorite is highly magnetic due to the presence of several per cent of iron-titanium oxides in the rock. Mafic minerals, comprising some 40% of the rock, consist of pale-yellow to brown euhedral hornblende, altered olivine and pyroxene. Euhedral plagioclase forms the remainder of the rock. The importance of volatiles in the late-stage crystallization of the intrusion is indicated by the occurrence of much interstitial chlorite, carbonate and pyrite.

Sharply succeeding the hornblende meladiorite is a layer of poikilitic hornblende meladiorite, about 22 m thick (Figure 5.7), which represents the most mafic-enriched part of the sill. In its lower part it is a highly distinctive black, pyritous, coarse-grained rock with hornblende crystals up to 25 mm long. The rock is dominated by areas in which large interlocking plates of dark reddish-brown hornblende poikilitically enclose highly altered olivine, clinopyroxene and plagioclase; the accessory minerals are iron-titanium oxides, apatite, and secondary actinolite, chlorite, pyrite and pumpellyite. This facies passes up into a more plagioclase-rich meladiorite in which the clinopyroxene is fresher. In the middle to lower parts the poikilitic meladiorite layer contains sporadic elliptical pegmatitic segregations. These show cores enriched in pink albite intergrown with large crystals and aggregates of white mica, pyrite and carbonate. In the south-eastern part of the sill (Figure 5.7), the poikilitic hornblende meladiorite forms metre-long pods within the hornblende diorite.

The topmost facies of the sill, about 24 m thick, consists of pale-grey, pyritous, coarse-grained hornblende diorite with prominent white plagioclase and black hornblende laths.

Interpretation

The Griff Hollow intrusion contains the complete assemblage of lithologies found in composite diorite sills of the late Ordovician Midlands Minor Intrusive Suite. Lamprophyres that occur along the sole and within the main body of the intrusion are interpreted as the chilled equivalents of the magmas which formed the diorite sills.

Previously, all of the Nuneaton sills were described as camptonites (e.g. Lapworth, 1898; Le Bas, 1968), but Hawkes (in Taylor and Rushton, 1971) noted that the diopsidic nature of the pyroxene, sodic composition of the plagioclase and absence of any obvious alkaline mineralogy is more in keeping with a classification as the spessartite variety of lamprophyre. However, Hawkes was incorrect to suggest that olivine is absent. The presence of olivine is compatible with the recent classification of spessartite as advocated by Rock (1987). Recent studies have shown that hornblende compositions in the Griff sill range from edenitic to pargasitic (Bridge *et al.*, 1998), and these are also compatible with a spessartite lineage for the Midlands Minor Intrusive Suite magmas.

Vertical mineralogical variations within the sill indicate that the amount of olivine and pyroxene remains approximately constant between the hornblende meladiorite and the succeeding

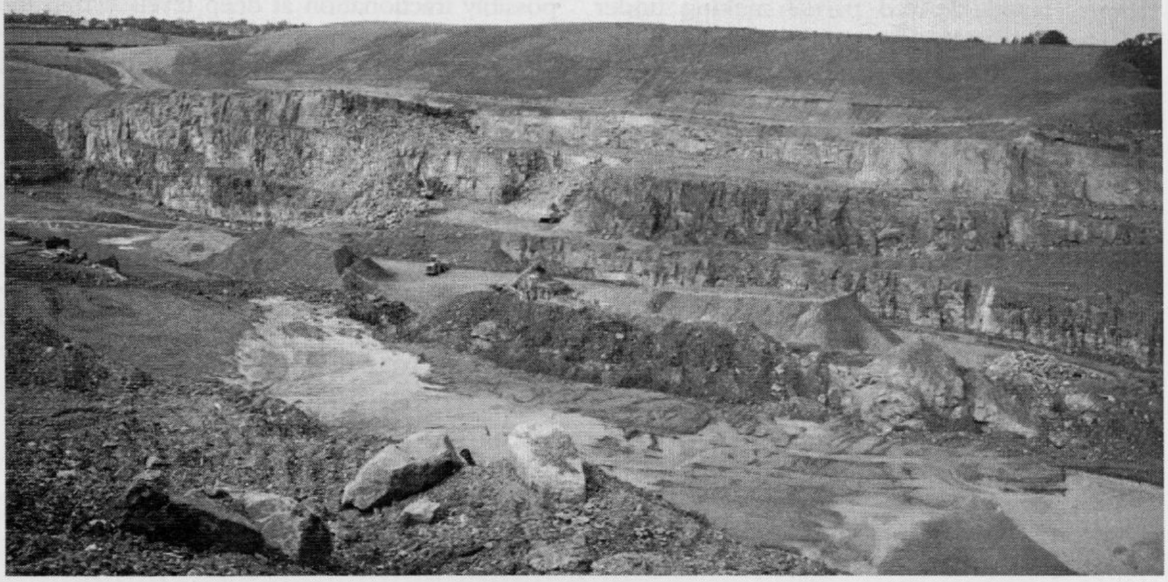

Figure 5.7 View of the western face of Griff No.4 Quarry. The base of the sill is at the foot of the lowest face, behind the stockpile in the centre of the photograph. The middle face, dark-grey in tone, exposes the poikilitic hornblende meladiorite layer and the upper face is in pale-grey hornblende diorite. The regular bedding above the latter represents the Coal Measures unconformably overlying the sill. (Photo: J. N. Carney.)

poikilitic hornblende meladiorite layer. The latter contains correspondingly larger amounts of interstitial hornblende, which suggests crystallization of a magma enriched in iron, magnesium and related elements. The coarse-grained, in places pegmatitic, texture of the poikilitic hornblende meladiorite further suggests relatively slow crystallization of hornblende in the presence of a volatile phase. These relationships show that in-situ fractionation involving mafic crystal accumulation is unlikely to have caused the compositional layering, and suggest that the intrusion formed by the multiple injection of related magma batches (Thorpe *et al.*, 1993). The field observations generally support multiple intrusion of these sills (e.g. Le Bas, 1968).

Geochemical data relevant to the petrological processes that contributed to the compositional diversity of the Griff Hollow sill are discussed in Thorpe *et al.* (1993) and Henney (in Bridge *et al.*, 1998). Henney showed that only one of the Griff Hollow rocks shows Eu enrichment, indicating that feldspar fractionation is unlikely to have occurred. Similarly, the values of MgO, Ni and Cr in most cases show a limited range indicating that they have undergone only minor fractionation, and in some rocks their abundances are comparable with those of unfractionated, primitive mantle-derived melts. Thorpe *et al.* (1993) also favoured a model involving low-degree, mantle-derived partial melting under volatile-rich conditions, with varying degrees of crystal fractionation of these liquids at the base of the crust or during ascent.

The tectonic setting of magma generation can be inferred from the geochemical data. Thorpe *et al.* (1993) noted that on the total alkali–silica diagram, the diorites and lamprophyres from Griff Hollow have an alkalic trend, with compositional affinities that span the basalt–trachyandesite fields and including types with normative olivine and hypersthene or nepheline. The rocks have high TiO_2 values relative to the South Leicestershire diorites, and Zr/Y and Zr concentrations appropriate to magmas generated in within-plate tectonic settings. However, the high La/Ta and Th/Ta ratios (Thorpe *et al.*, 1993), and high Ba/Ta (Henney, in Bridge *et al.*, 1998) also suggest the involvement of a subduction zone component in their genesis. It is considered probable that the Midlands Minor Intrusive Suite originated from lithospheric mantle previously enriched during Ordovician subduction, and subjected to low-degree partial melting during cessation of subduction. This occurred at a time when the accretion of Caledonian orogenic terranes had enlarged the Midlands cratonic crust (Thorpe *et al.*, 1993).

Conclusions

The Griff Hollow GCR site exposes diorites and lamprophyres belonging to the late Ordovician Midlands Minor Intrusive Suite, and emplaced into the Upper Cambrian Stockingford Shale Group. The site contains a typical example of a composite layered hornblende diorite sill, consisting of a lamprophyric sole, passing upwards into a hornblende-enriched facies and pale hornblende diorite. The diversity of rock types has not arisen from in-situ crystal fractionation, but from processes involving partial melting and possibly fractionation at deep levels within the crust or upper mantle, followed by the multiple intrusion of genetically related magma batches. The Griff Hollow sill belongs to essentially the same late Ordovician (Caledonian) magmatic episode as the quartz-bearing South Leicestershire diorites, but differs petrographically and geochemically, and may have been emplaced slightly later, when the tectonic setting of this region was undergoing transition from a subduction-controlled to a within-plate type of regime.