Carboniferous and Permian Igneous Rocks of Great Britain

North of the Variscan Front

D. Stephenson*,

S.C. Loughlin*,

D. Millward*,

C.N. Waters+

and

I.T. Williamson+

*British Geological Survey, Murchison House, West Mains Road, Edinburgh EH9 3LA.
+British Geological Survey, Kingsley Dunham Centre, Keyworth, Nottingham NG12 5GG.

GCR Editor: D. Palmer

JOINT NATURE CONSERVATION COMMITTEE

British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Chapter 3

Dinantian volcanic rocks of the Northumberland, Solway and Tweed basins

INTRODUCTION

D. Millward and I.T. Williamson

Tournaisian to early Visean basaltic volcanism occurred locally along the margins of the Northumberland, Solway and Tweed basins during the initial phase of rapid, fault-controlled back-arc extension of the crust to the north of the Variscan Front. The E–W-orientated basins are markedly asymmetrical and lie between 'blocks' of deformed and weakly metamorphosed Lower Palaeozoic basement rocks. To the north lies the Southern Uplands, to the south are the Lake District and Alston blocks, and separating the Tweed and Northumberland basins is the Cheviot Block, which also comprises a succession of Early Devonian lavas (Figure 3.1; Kimbell *et al.*, 1989; Leeder *et al.*, 1989; Chadwick *et al.*, 1995). Ordovician to Early Devonian granitic plutons are major intrusions within the Cheviot, Lake District and Alston blocks.

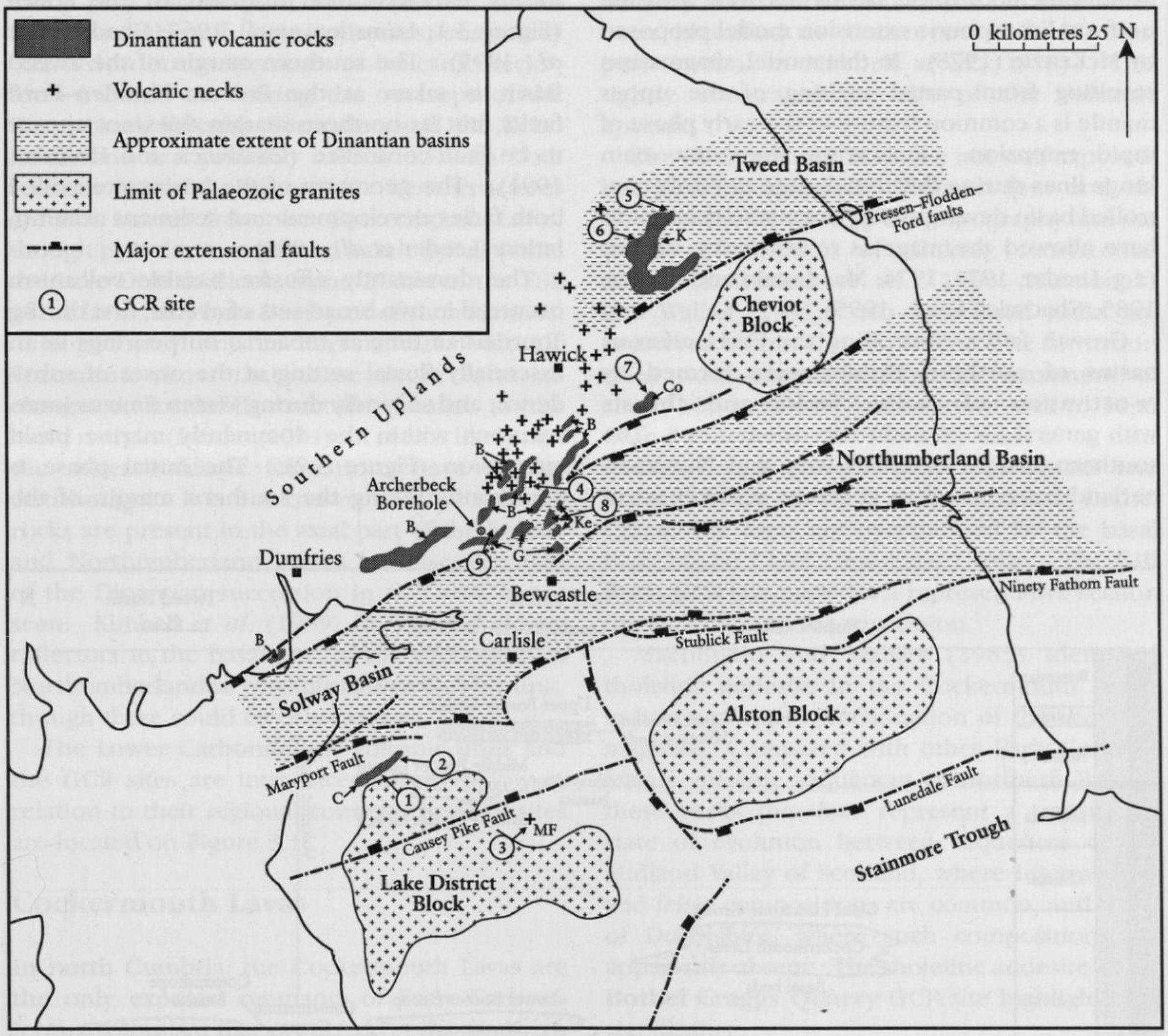

Figure 3.1 Map of the Solway, Northumberland and Tweed basins showing the outcrops of Dinantian volcanic rocks and the major structural components. GCR sites: 1 = Gill Beck; 2 = Bothel Craggs Quarry; 3 = Little Mell Fell Quarry; 4 = Langholm–Newcastleton Hills; 5 = Lintmill Railway Cutting; 6 = Hareheugh Craigs; 7 = Cottonshope Head Quarry; 8 = Kershope Bridge; 9 = River Esk, Glencartholm. (Volcanic units are as follows: B = Birrenswark Volcanic Formation; C = Cockermouth Lavas; Co = Cottonshope Basalts; G = Glencartholm Volcanic Beds; K = Kelso Lavas; Ke = Kershopefoot Lavas; MF = Mell Fell Vent.) Information from published sources including Chadwick and Holliday (1991); Chadwick *et al.* (1995); Leeder (1974); and British Geological Survey (Tectonic map of Britain, Ireland and adjacent areas, 1996).

The Northumberland and Solway basins lie above the inferred line of the Iapetus Suture, marking the junction of the former continents of Laurentia and Avalonia, which were finally locked together during the latest phase of the Caledonian Orogeny (see Chapter 1). Leeder (1971, 1974) was the first to propose that Dinantian magmatism preceded the structural development of the basins, invoking Bott's (1964) model of mantle flow. Since then, studies of subsidence history (e.g. Leeder and McMahon, 1988; Kimbell *et al.*, 1989) have shown that the development of these basins fits well with the uniform lithospheric extension model proposed by McKenzie (1978). In this model, magmatism resulting from partial melting of the upper mantle is a common feature of the early phase of rapid extension. Fracturing along the main hinge lines during this initial stage not only controlled basin development, but is also thought to have allowed the magmas to reach the surface (e.g. Leeder, 1971, 1974; Macdonald and Walker, 1985; Chadwick *et al.*, 1995).

Growth faults controlling the Carboniferous basins of northern Britain were formed by re-activation of earlier faults and thrusts with general ENE Caledonian orientations. The southern margin of the Solway and Northumberland basins is taken at the *en échelon* set of normal faults that includes the Maryport Fault in Cumbria and the Stublick and Ninety Fathom faults in Northumberland. The thickest Lower Carboniferous strata in these basins occur adjacent to these faults and the maximum fault displacement, measured from the top of the Lower Palaeozoic basement, is 5000 m down to the north. The Lower Carboniferous sedimentary succession thins markedly towards the northern, hinge-like margin, and the faults there are interpreted to be antithetic structures to the southern faults; syn-extensional displacement locally exceeds 1000 m down to the south (Figure 3.1; Lumsden *et al.*, 1967; Chadwick *et al.*, 1995). The southern margin of the Tweed Basin is taken at the Pressen–Flodden–Ford faults, but its northern margin does not appear to be fault-controlled (Chadwick and Holliday, 1991). The geometry of the basins controlled both facies development and sediment accumulation (Leeder *et al.*, 1989).

The dominantly effusive basaltic volcanism occurred in two broad sets of events, first during Tournaisian time as subaerial outpourings in an essentially fluvial setting at the onset of subsidence, and secondly during Visean time as intercalations within the dominantly marine basin succession (Figure 3.2). The initial phase is represented along the southern margin of the

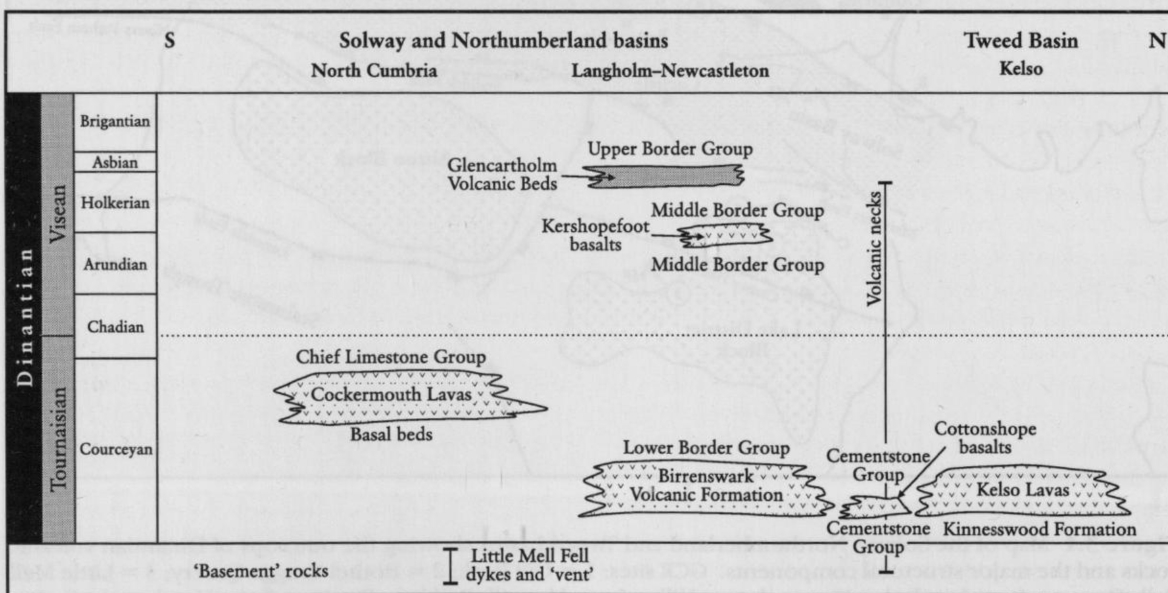

Figure 3.2 Stratigraphy of the volcanic rocks of the Solway, Northumberland and Tweed basins. The range of strata cut by intrusions and volcanic rocks is also shown. After Gawthorpe *et al.* (1989).

basins only by the Cockermouth Lavas, whereas on the northern margin, adjacent to the Southern Uplands, there are the Birrenswark Volcanic Formation and the Kelso Lavas. The Cottonshope basalts, located on the south-western flanks of the Cheviot Block, also belong to this episode. The later phase is known only from the northern margins and comprises the Kershopefoot basalts and the Glencartholm Volcanic Beds. In the Isle of Man, basalt and basaltic pyroclastic rocks of the Brigantian Scarlett Volcanic Formation (Dickson *et al.*, 1987) may also be part of this phase. A substantial number of intrusive bodies, commonly referred to in the literature as 'volcanic necks', form a broad arc linking the outcrops of the Birrenswark Volcanic Formation and the Kelso Lavas, and are probably associated with both volcanic episodes (Figure 3.1). Vent structures are not known from the Cockermouth Lavas, though pyroclastic rocks and basalt dykes within the Lake District Block, some 27 km to the ESE of the lavas, may have been part of such features.

Isopachytes on the Birrenswark Volcanic Formation show that these rocks form an elongated, localized structure parallel to the basin margin (Leeder, 1974). It seems likely that the other volcanic formations have similar distributions. It is not known whether volcanic rocks are present in the axial part of the Solway and Northumberland basins because the base of the Dinantian succession in this area is not seen. Kimbell *et al.* (1989) interpreted strong reflectors in the basal part of the succession in Northumberland as possibly from a basaltic unit, though there could be other causes.

The Lower Carboniferous volcanic units and the GCR sites are introduced briefly below in relation to their regional context; the GCR sites are located on Figure 3.1.

Cockermouth Lavas

In north Cumbria, the Cockermouth Lavas are the only exposed remnants of Early Carboniferous volcanism that occurred on the southern margin of the Northumberland and Solway basins. The sequence of tholeiitic, olivine-phyric basalt and subordinate andesite, up to 105 m thick, crops out for about 12 km north-eastwards from Cockermouth. These rocks form a southerly facing escarpment on the northern side of the River Derwent, only a few kilometres to the south of the Gilcrux and Maryport faults that mark the basin margin (Figure 3.1). The subcrop extent of the Cockermouth Lavas is unknown; a prominent magnetic anomaly in this area is more likely to be attributable to the concealed westward extent of the Ordovician Eycott Volcanic Group, than to the weakly magnetic Cockermouth Lavas (Millward *et al.*, 1999).

The volcanic rocks are within the basal part of the Dinantian succession in Cumbria, resting conformably on conglomerate and sandstone of the Basal Beds, and overlain by the lowest strata of the Chief Limestone Group. The sedimentary rocks above and below the lavas have been identified as Courceyan (C.E. Butcher, pers. comm. in Mitchell *et al.*, 1978). This tightly constrains the age of the volcanic episode.

The Cockermouth Lavas are not well exposed, but probably comprise between four and six flows, based on the trap-like topography and the patchy distribution of clinkery, scoriaceous zones (Eastwood *et al.*, 1968; Macdonald and Walker, 1985). No pyroclastic rocks are preserved within the sequence. The formation thins north-eastwards from its maximum of about 105 m in the Cockermouth area to 30 m near Sunderland (NY 170 352) and 40 m near Bothel Craggs (NY 149 342) (Macdonald and Walker, 1985). A little to the north of Bothel Craggs the lavas are overstepped by the basal beds of the Chief Limestone Group. The **Gill Beck** GCR site provides a representative section through most of the succession.

Macdonald and Walker (1985) identified tholeiitic andesite in the Cockermouth Lavas, indicating limited fractionation of the tholeiitic magmas. Compared with other Early Carboniferous volcanic sequences of northern Britain, these rocks therefore represent a transitional state of evolution between sequences of the Midland Valley of Scotland, where intermediate and felsic compositions are common, and those of Derbyshire, where such compositions are apparently absent. The tholeiitic andesite in the **Bothel Craggs Quarry** GCR site highlights this significance.

Basalt dykes cropping out on Little Mell Fell, 27 km to the ESE of the Cockermouth Lavas, were first described by Capewell (1954). He suggested that these rocks were associated with the early Dinantian volcanic activity. Macdonald and Walker (1985) later recognized geochemical similarities between the dykes and the Cockermouth Lavas, which supported this theory. The basalt dykes are represented by the **Little Mell Fell Quarry** GCR site, which also includes exposures of unbedded lapilli-tuff. These are the only recorded occurrence of pyroclastic rocks associated with Early Carboniferous volcanism on the southern side of the basin.

Birrenswark Volcanic Formation and Kelso Lavas

The earliest volcanic eruptions on the northern margin of the basin are represented by the Birrenswark Volcanic Formation and the Kelso Lavas. Both sequences consist predominantly of subaerial basaltic lavas, with rare hawaiite or mugearite. Individual flows have massive central portions, scoriaceous upper parts and lobate or rubbly bases. Some lava surfaces are reddened and locally they are overlain by thin palaeosols (boles). The lavas are intercalated with thin beds of sedimentary or pyroclastic rock. For example, the Birrenswark Volcanic Formation includes thin beds of red sandstone and siltstone (Pallister, 1952; Elliott, 1960; Lumsden *et al.*, 1967), and interbedded volcaniclastic rocks are reported from parts of the Kelso Lavas (Eckford and Ritchie, 1939; Tomkeieff, 1945, 1953).

The Birrenswark Volcanic Formation comprises a series of unconnected NE-trending outcrops, extending for a distance of over 70 km from Kirkbean, south of Dumfries, to near Saughtree south-east of Hawick (Figure 3.1). These rocks overlie either Lower Palaeozoic basement or Lower Carboniferous rocks of Upper Old Red Sandstone facies, and are overlain conformably by Tournaisian sedimentary rocks of the Lower Border Group (Lumsden *et al.*, 1967). The succession of olivine basalt, basaltic hawaiite and hawaiite lavas is intercalated with some reddened siltstone and sandstone beds up to 10 m thick. A whole-rock K-Ar radiometric age of 361 ± 7 Ma for the Birrenswark Volcanic Formation was obtained by De Souza (1982). The **Langholm–Newcastleton Hills** GCR site is representative of the Birrenswark Volcanic Formation and contains several excellent stream sections through this otherwise poorly exposed formation.

The maximum thickness of the formation, *c.* 90 m, is recorded around Birrenswark Hill, south-west of Langholm. Leeder (1974) showed that the thickness of the lavas varies systematically across the area, and that the lavas originally extended over an area of approximately 1830 km^2. This inferred distribution coincides broadly with the south-west part of the Upper Old Red Sandstone fluvial basin (Leeder, 1974). However, the isopachytes also show that the lavas occur in two distinct areas, south-west and north-east of Langholm, separated by a narrow zone just west of the town where Tournaisian sedimentary rocks rest directly on Silurian basement (Nairn, 1956). Leeder (1974) attributed this either to the persistence of a topographical high, implying two separate basins, or to uplift and erosion after the volcanism.

The Kelso Lavas form a roughly horseshoe-shaped outcrop between the Blackadder Water near Duns and Carham-on-Tweed, north-west of the Cheviot massif in the Tweed Basin. The lavas overlie Upper Old Red Sandstone sedimentary rocks and are thought to be of Tournaisian age (Figure 3.2). A succession of up to 12 basalt, basaltic hawaiite and hawaiite lavas are intercalated with thin tuffs and sedimentary rocks (Smedley, 1986a). The sequence is generally poorly exposed, though in some parts a terraced or 'trap' topography is well developed locally. According to Eckford and Ritchie (1939), the succession is about 120 m thick. Tomkeieff (1953) showed that the lower flows are mostly feldspar phyric in contrast to the upper ones, which contain olivine and clinopyroxene phenocrysts. The rocks are pervasively altered. The Kelso Lavas are represented by the **Lintmill Railway Cutting** GCR site, which is situated alongside the Blackadder Water.

The Birrenswark Volcanic Formation and the Kelso Lavas clearly accumulated at separate centres (Leeder, 1974), though they were probably erupted penecontemporaneously. The presence of palaeosols and interbedded sedimentary rocks is taken to indicate a subaerial environment with periods of relative quiescence between eruptions. Most of the volcanic activity is inferred to have been quietly effusive.

Cottonshope basalts

On the south-western flanks of the Cheviot massif, relatively small outcrops of amygdaloidal tholeiitic, olivine-phyric basalt are present in Cottonshope Burn, Spithope Burn, at Hungry Law and between the Bareinghope Burn and the Chattlehope Burn. These are the Cottonshope basalts, which comprise three lavas with a total thickness of 24 m. These volcanic rocks are represented by the **Cottonshope Head Quarry** GCR site. They are interbedded with fluvial and lagoonal sedimentary rocks of the Cementstone Group of Northumberland (Miller, 1887; Taylor *et al.*, 1971), which is probably equivalent to the Lower Border Group farther west. Some uncertainty has surrounded the age of the Cottonshope basalts. They lie only about 100 m beneath the top of the Cementstone Group in this area and this datum probably corresponds approximately with the top of the Tournaisian Series. However, evidence first recorded here in the GCR site report suggests that the basalts may be early Tournaisian in age and therefore probably part of the Birrenswark–Kelso event.

Kershopefoot basalts

The Kershopefoot basalts crop out in the area between Langholm and Kershope Burn on the Anglo–Scottish border. The volcanic rocks are interbedded with the uppermost strata of the Visean Middle Border Group and represent a resurgence of volcanic activity following the widespread marine sedimentation that inundated the earlier Birrenswark Volcanic Formation. Numerous flows of either basalt, basaltic hawaiite or hawaiite composition (Smedley, 1986a) comprise a succession that is generally 30–36 m thick (Lumsden *et al.*, 1967; Day, 1970). These rocks have generally been assumed to be extrusive, though some doubt was expressed by Lumsden *et al.* (1967) because contacts are not exposed. These rocks are particularly well exposed at the **Kershope Bridge** GCR site.

Glencartholm Volcanic Beds

At the base of the Upper Border Group in the Langholm district, the Glencartholm Volcanic Beds are the youngest known products of syn-extensional volcanism associated with the Solway, Northumberland and Tweed basins. In contrast to the earlier phases of Dinantian volcanism, the formation almost entirely comprises interbedded basaltic and trachytic pyroclastic rocks, along with other volcaniclastic and sedimentary units (Lumsden *et al.*, 1967). There are a few local occurrences of basaltic lavas, up to 15 m thick. The thickness of the Glencartholm Volcanic Beds locally reaches about 180 m. Bedded volcaniclastic rocks in a similar stratigraphical position have been proved in the Archerbeck borehole about 8 km south of Langholm (Lumsden and Wilson, 1961), and are represented in the Bewcastle area, by the Oakshaw Tuff (Day, 1970), suggesting that these volcanic deposits are widespread. The volcanism occurred within a mainly marine environment, though periodic emergence is shown by the presence of seatearths and coals (Lumsden *et al.*, 1967).

The Glencartholm Volcanic Beds are of Visean age, though the ages determined by different palaeontological methods are not consistent. Dineley and Metcalf (1999) suggested an early Visean age based on the faunal macropalaeontology, whereas according to Cleal and Thomas (1995), a late Visean age is more consistent with palaeobotanical data; foraminiferans from the sequence suggest a position near the Holkerian–Asbian boundary (George *et al.*, 1976).

The fragmental volcanic rocks are readily weathered and thus poorly exposed, except in stream sections. The **River Esk, Glencartholm** GCR site is representative of the Glencartholm Volcanic Beds. This site is also highly significant because of the unusual fish and arthropod fauna from shallow marine or lagoonal mudstone interbeds; these were first reported by Peach and Horne (1903) (see Dineley and Metcalf, 1999).

Volcanic necks

More than 50 pipe-like bodies of pyroclastic rocks lie within an arc that broadly connects the outcrops of the Birrenswark Volcanic Formation and the Kelso Lavas (Figure 3.1; Leeder, 1974). Some of the pipes are cut by plugs of basalt and some of the intrusions are composite. They occur within Dinantian or adjacent Silurian rocks, though none cut strata younger than the Glencartholm Volcanic Beds and they are not known from Dinantian rocks in the centre and south of the basin (Lumsden *et al.*, 1967). These masses have long been interpreted as marking the site of volcanic conduits, and this remarkable development was referred to as the 'Border Puy-country' by Geikie (1897), because of the perceived similarity with the spectacular Puy landscape in central France.

Plugs of basaltic rocks are numerous and some of these, particularly in the Kelso area, are composite intrusions of basalt, hawaiite and/or mugearite (Macdonald, 1975). However, in contrast to the entirely basic lava successions, the intrusions also include a number of alkaline and peralkaline felsic rocks. For example, the well-known laccolith complex of the Eildon Hills, near Melrose, comprises basaltic, trachytic and riebeckite-microgranitic components (McRobert, 1914) and other alkaline felsic intrusions occur south-west of Duns (Irving, 1930). About 10 km SSW of Hawick, the Skelfhill Pen intrusion is significant because of the association there of quartz-trachyte, aegirine trachyte and riebeckite-aegirine phonolite (McRobert, 1920). Many of the felsic intrusions are aligned about major NE-trending faults and some dykes define a diffuse swarm with a similar trend, suggesting structural control on their emplacement, as in the Campsie Fells and Garleton Hills (Upton, 1982).

The igneous clasts in the breccia-filled pipes include vesicular basaltic glass and crystalline olivine basalt, most of which is thoroughly decomposed. A single block of altered peridotite is recorded from the Black Burn–Rough Gill Vent (Lumsden *et al.*, 1967). There are also variable quantities of sedimentary rock fragments, including sandstone, mudstone, limestone and chert.

The basaltic to mugearitic volcanic necks in the Scottish Borders region have long been considered the most likely sources of the lavas and pyroclastic rocks of the Tournaisian Birrenswark Volcanic Formation and Kelso Lavas (e.g. McRobert, 1920). It is also possible that the felsic intrusions may be associated with this early volcanism, since an Ar-Ar date of 352.5 ± 1.4 Ma has been obtained recently from sanidine in a trachyte from the Eildon Hills (A.A. Monaghan and M.S. Pringle, pers. comm., 2002). However, many of the pyroclastic breccia-filled bodies north-east of Langholm cut upper Tournaisian sedimentary rocks and hence these may represent the sub-volcanic sources of the Glencartholm Volcanic Beds and perhaps the Kershopefoot basalts (McRobert, 1920).

Volcanic necks cutting the Birrenswark Volcanic Formation are described in the **Langholm–Newcastleton Hills** GCR site. The **Hareheugh Craigs** GCR site is a particularly good example of a composite intrusion, possibly associated with emplacement of the Kelso Lavas.

GILL BECK, CUMBRIA (NY 149 342)

D. Millward

Introduction

The Lower Carboniferous (Dinantian) Cockermouth Lavas are probably best displayed in the Gill Beck GCR site, south of Blindcrake and about 4.5 km north-east of Cockermouth (Figure 3.3). There, a sequence of basalt lavas,

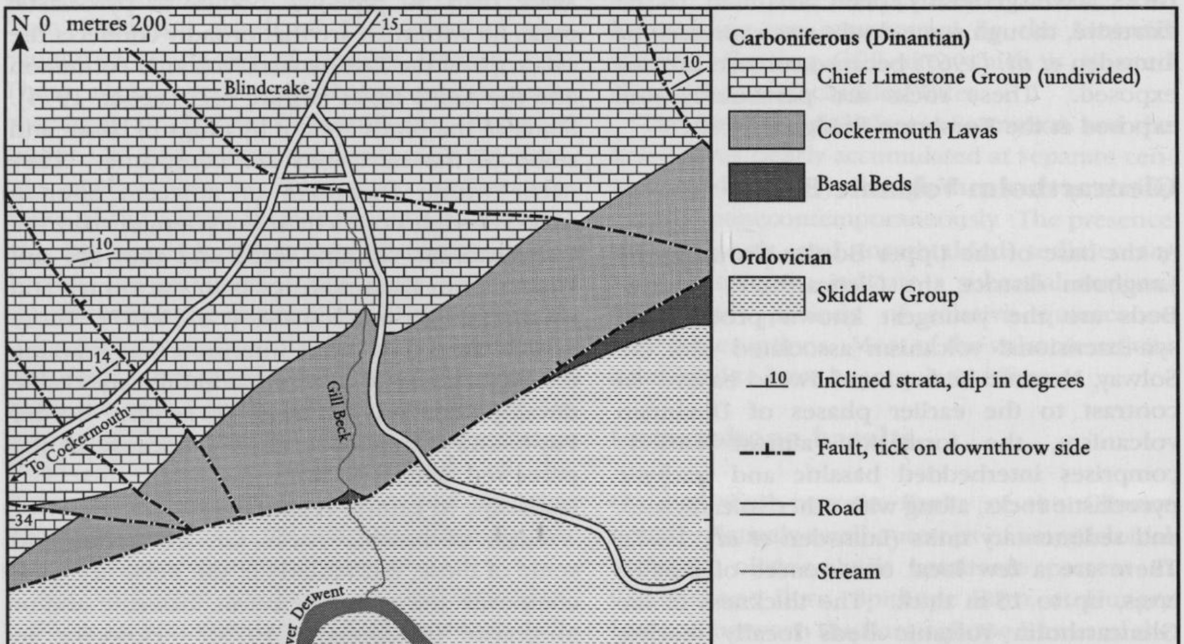

Figure 3.3 Map of the area around the Gill Beck GCR site. Based on British Geological Survey 1:10 000 sheets NY 13 SE; and NY 13 SW (both 1991).

approximately 67 m thick, overlies basal Carboniferous conglomerates referred to formally as the Basal Beds. Above the lavas are bedded mudstone, limestone and sandstone at the base of the Chief Limestone Group. The Cockermouth Lavas are the only known example of effusive basaltic volcanism focused upon the southern hinge-zone margin of the Solway Basin. In general, the volcanic rocks are poorly exposed and this GCR site is especially valuable in providing good stream exposure.

The presence of amygdaloidal 'greenstones' in Gill Beck was recorded by the primary geological survey of the area during the 19th century, and the stream exposures are mentioned in accounts of the Cockermouth Lavas by Eastwood (1928), Eastwood *et al.* (1968), and Macdonald and Walker (1985). The GCR site is included within the British Geological Survey's 1:50 000 Sheet 23, Cockermouth (1997). The age of the Cockermouth Lavas is tightly constrained to the Courceyan (C.E. Butcher, pers. comm. in Mitchell *et al.*, 1978). This is indicated by the presence of CM Zone miospore assemblages in sedimentary rocks from the Chief Limestone Group overlying the lavas at Gill Beck. Nearby, exposures of the Basal Beds underlying the lavas have also yielded spores of the same zone.

The geochemistry of the Cockermouth Lavas has been described and interpreted by Macdonald and Walker (1985); a single whole-rock analysis from Gill Beck is cited by these authors. Tholeiitic andesite has been recognized within the sequence at Gill Beck and this has implications for the petrogenesis of the Cockermouth Lavas (Macdonald and Walker, 1985) (see **Bothel Craggs Quarry** GCR site report).

Description

The following description is based on the published accounts listed above. The lithostratigraphical nomenclature follows that used on the British Geological Survey's Sheet 23, Cockermouth (1997). The site consists of a stream section, within which the Carboniferous rocks dip gently to the NNW (Figure 3.3). The base of the lava succession is not exposed, though a small exposure of conglomerate is seen beneath its inferred position (Figure 3.4). The

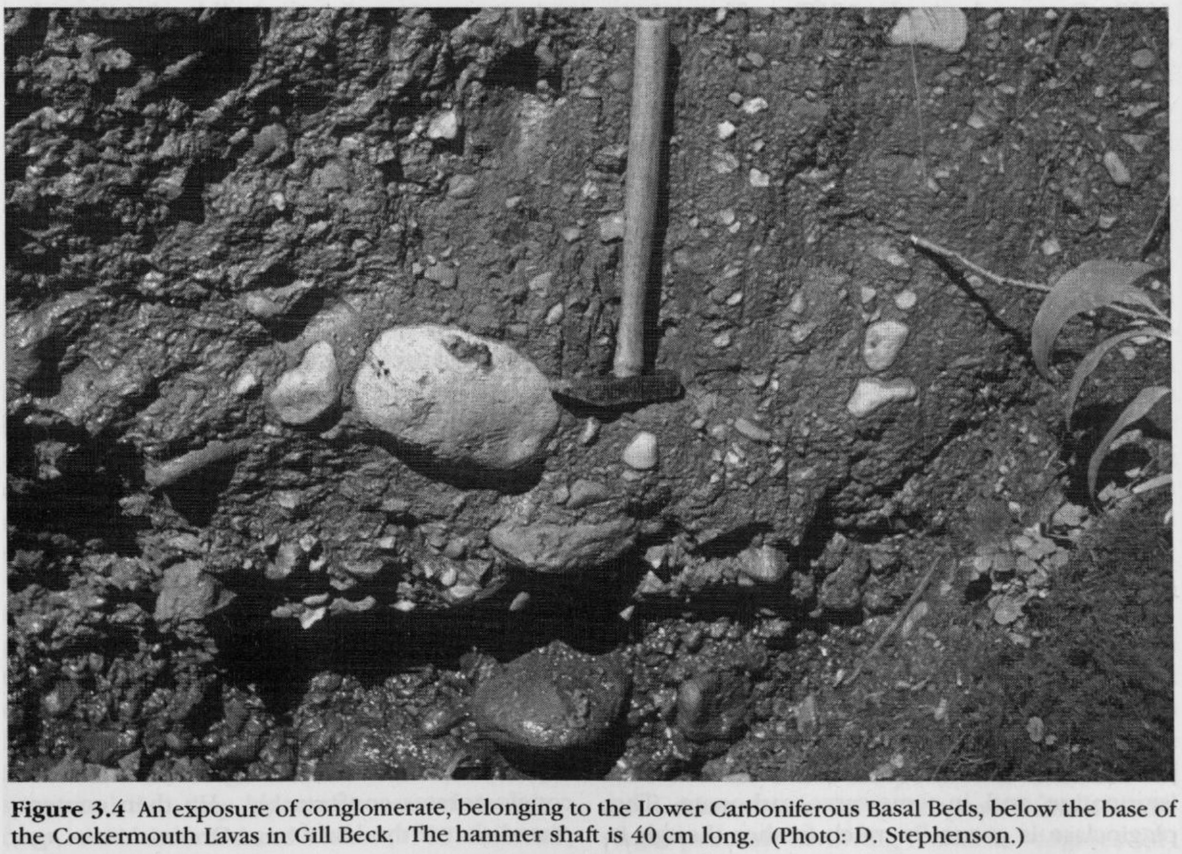

Figure 3.4 An exposure of conglomerate, belonging to the Lower Carboniferous Basal Beds, below the base of the Cockermouth Lavas in Gill Beck. The hammer shaft is 40 cm long. (Photo: D. Stephenson.)

top of the succession is also not exposed, though mudstones and thin limestones near the base of the Chief Limestone Group are seen along the stream close to the highest exposure of the lavas (Eastwood, 1928). Here the Cockermouth Lavas are about 67 m thick.

On field maps in the British Geological Survey archive, T. Eastwood recorded the basalts as variably massive to highly scoriaceous. He described most of the rocks as compact to slightly amygdaloidal, but especially amygdaloidal and scoriaceous rocks are characteristic of the top and base of the flows; in some places he described the distribution of scoriaceous rock as 'haphazard' (Eastwood, 1928). Though vesicles are commonly distorted, there is little evidence for linear structures indicating directions of flow. The vesicles are mainly filled with carbonate or various forms of silica. The more massive rocks in the centres of the lavas are dark blue or grey and finely granular. Intercalations of pyroclastic or sedimentary rocks have not been recorded from the sequence, but the presence of at least four lavas may be inferred from the distribution of scoriaceous basalt within the section.

The petrography of the Cockermouth Lavas was first outlined by H.H. Thomas (in Eastwood, 1928; Eastwood *et al.*, 1968). The microcrystalline basalts typically comprise plagioclase, augite and iron oxide with variable amounts of olivine microphenocrysts; some rocks contain plagioclase and/or augite phenocrysts. Most of the rocks have ophitic or sub-ophitic texture, and in some of these the tabular plagioclase laths form a sub-parallel fabric; intergranular texture is seen sporadically. Geochemical analyses reported by Macdonald and Walker (1985) show that both basalt and andesite are present in the Gill Beck succession. They described the andesite from Gill Beck as aphyric and fine grained, comprising plagioclase laths, granular, partially serpentinized augite and abundant iron oxide; interstitial quartz, alkali feldspar and chlorite are also present. The plagioclase defines a marked flow texture in the andesite.

The basalts are noted for their pervasive secondary alteration. Olivine is entirely replaced by an aggregate of 'serpentine', chlorite, green mica, quartz, opaques and carbonate. The pyroxene is partially fresh in places, though it is normally altered to 'serpentine' and, in some cases, carbonate. The plagioclase is generally much fresher though it may be albitized or replaced by carbonate. Loveland and Bendelow (1984) reported celadonite-like grains in highly altered basalt nearby at Bridekirk; this was the first recorded occurrence of the mineral in England. Macdonald and Walker (1985) also noted that, as a result of the alteration, Ca-poor pyroxene has not been identified in these rocks even though its presence may be suspected by analogy with compositionally similar rocks in the Dinantian lavas of Derbyshire.

Despite the intense mineralogical alteration of the basalts, magmatic characteristics are retained, particularly with respect to the incompatible minor- and trace-element abundances (Ti, P, Zr, Nb, Ce, Y) (Macdonald and Walker, 1985). The Cockermouth Lavas have a relatively small range in silica saturation, attributable to magmatic processes rather than alteration. This is indicated by the negative correlation of the ratios Zr/Y and Nb/Y, and positive correlation of Zr/Nb with increasing silica saturation, which is typical of basalts as a whole. The basalts are quartz- and hypersthene-normative and may be described as quartz tholeiitic. Plots of incompatible elements show that the Cockermouth Lavas form a very coherent suite of genetically related rocks. However, the range of variation for some elements is very wide (e.g. Nb 9–32 ppm and Zr 70–258 ppm) (Macdonald and Walker, 1985).

Interpretation

The Cockermouth Lavas were considered to be of Ordovician age by J.C. Ward and J.G. Goodchild who made the primary geological survey of the Cockermouth area, late in the 19th century. These basalts were thought to be part of the same volcanic episode that produced the widespread Eycott and Borrowdale volcanic groups (at this time these two groups were included under the latter name). By contrast, a Carboniferous age was assigned to the more extensive conglomerate, now formally the Basal Beds. Exposures of the conglomerate, for example in Gill Beck, which are apparently located below the basalts, were considered to be faulted against the base of the basalts.

In re-surveying the area, Eastwood (1928) found that, although the junction is not exposed, the basalts undoubtedly overlie the conglomerates conformably. He then contemplated that if the lavas were Ordovician in age, the conglomerate must be of 'early Borrowdale age' and thus also Ordovician. However, the petrographical descriptions by H.H. Thomas (in Eastwood, 1928) showed that the basalts contain phenocrysts of olivine and thus differ markedly from the Eycott and Borrowdale volcanic group rocks. Eastwood noted that there are also other lithological differences between the volcanic rocks, but that the conglomerate has some similarity with the Mell Fell Conglomerate farther east in Cumbria. Considering these observations, Eastwood (1928) then proposed that the basalts are probably Carboniferous in age and should be designated as the Cockermouth Lavas. A Dinantian (Courceyan) age has since been confirmed from spore assemblages obtained from the sedimentary rocks, both beneath and above the basalts (C.E. Butcher, pers. comm. in Mitchell *et al.*, 1978).

The variably clinkery and scoriaceous character of the basalt sheets supports the widely held interpretation of these rocks as lavas. Furthermore, the occurrence in a stream (NY 128 327) to the north-east of Wood Hall of 'a roughly lenticular mass of red and green marl...interspersed with lumps of very rotten amygdaloidal rock' was interpreted by Eastwood (1928) to be bole-like, indicating subaerial weathering of the basalt. No evidence has come to light that contradicts this interpretation. However, in the absence of unequivocal evidence for the nature of the uppermost contacts of the sheets, it is possible that some sills may be present. One piece of evidence that may be pertinent to the method of emplacement of the sheets is described by Eastwood *et al.* (1968). Near Redmain, south-west of the GCR site, they reported that the upper zone of a basalt sheet is cut by narrow veins and irregular patches of dark-purple flinty material that die out downwards, while some appear to pass upwards into 'bole'. Eastwood *et al.* offered no explanation, but it is possible that these are sedimentary enclaves.

The apparent absence of volcaniclastic rocks from the sequence suggested to Eastwood (1928) and Macdonald and Walker (1985) that Carboniferous volcanism in the area was mildly effusive and perhaps from fissure-type vents. Possible eruption sites have not been identified in the field, though Eastwood *et al.* (1968) suggested that they lay to the west of the outcrop, and Macdonald and Walker (1985) inferred a fissure or series of vents along the outcrop. However, if the volcanism is associated with crustal extension and basin formation, then the hinge-line faults such as the Maryport and Gilcrux faults located to the north of the Cockermouth Lavas outcrop (Figure 3.1) must be considered as potential magma channels. Effusive to mildly explosive volcanism with extensive lavas is typical in extensional tectonic regimes such as in the Solway and Northumberland basins. The apparent absence of pyroclastic rocks from the subaerial Cockermouth Lavas does not necessarily indicate that none were erupted; any accumulated tephra deposits would have been localized as small cones, and would have been subjected to rapid erosion and possibly complete removal. Further, if the vents were located along the basin hinge-line fault system, then the present outcrop of the Cockermouth Lavas is at least 2 km from these, mostly well outside the depositional range for mildly explosive eruptions.

The Cockermouth Lavas are unlikely to represent primary basalts because of their characteristically low Mg numbers ($100 \times Mg/(Mg + Fe)$ 60). Furthermore, on the diopside–olivine–hypersthene–nepheline–quartz phase diagram, representing the crystallization of basaltic liquids, the normative compositions of the Cumbrian rocks plot close to the cotectic at 1 atmosphere. However, Macdonald and Walker (1985) argued that the basalts cannot represent a simple low-pressure fractionation series, because the levels of incompatible elements, such as Zr, Nb, P, Ce and Y, do not decrease systematically with MgO, which is used as an index of fractionation. On the contrary, the most magnesian rocks contain the highest levels of K, Ti, P and incompatible trace elements. Thus, in addition to low-pressure fractionation, the chemical variation in the Cockermouth Lavas must have resulted from variable amounts of partial melting, or from fractionation at higher pressures.

Macdonald and Walker (1985) concluded that the Cockermouth Lavas were probably generated from upper-mantle sources; immobile trace-element ratios such as Zr/Nb, Zr/Y and Ce/P_2O_5 do not suggest that the source region was heterogeneous. Macdonald and Walker (1985) also suggested that, like the Dinantian lavas of Derbyshire, compositional variations in the Cockermouth Lavas resulted from a two-stage process involving variable degrees of partial melting to produce parent liquids with a range of silica saturation, followed by low-pressure fractional crystallization, probably in the upper crust.

Conclusions

The Gill Beck GCR site is representative of the Tournaisian Cockermouth Lavas, the only exposed example of volcanic rocks of this age along the southern margin of the Solway Basin. The formation comprises tholeiitic olivine-phyric basalt and aphyric andesite, and is approximately 67 m thick. At least four lavas are present, but no pyroclastic rocks are preserved. The volcanic rocks conformably overlie conglomerates at the base of the Carboniferous succession in Cumbria (the Basal Beds), and are overlain by sedimentary rocks of the Chief Limestone Group. The basalt magmas are thought to have evolved through variable degrees of partial melting of upper-mantle source rocks, followed by moderate- to low-pressure crystal fractionation.

BOTHEL CRAGGS QUARRY, CUMBRIA (NY 186 371)

D. Millward

Introduction

Tholeiitic andesite in the Lower Carboniferous (Dinantian) Cockermouth Lavas is exposed in the small quarry on the west side of the A591 road, near Bothel Craggs, about 1.5 km SSE of the village of Bothel in Cumbria (Figure 3.5). The Bothel Craggs Quarry GCR site is at the eastern extent of the Cockermouth Lavas, the only exposed example of effusive volcanism localized along the southern hinge-zone margin of the Solway Basin.

The Cockermouth Lavas were first described by Eastwood (1928) and by Eastwood *et al.* (1968), and the Bothel Craggs Quarry GCR site is included within the British Geological Survey's 1:50 000 Sheet 23, Cockermouth (1997). Geochemical analysis of the lava from this quarry by Macdonald and Walker (1985) showed that it is a tholeiitic andesite, which has implications for the petrogenesis of the Cockermouth Lavas in the wider context of Early Carboniferous magmatism in Great Britain.

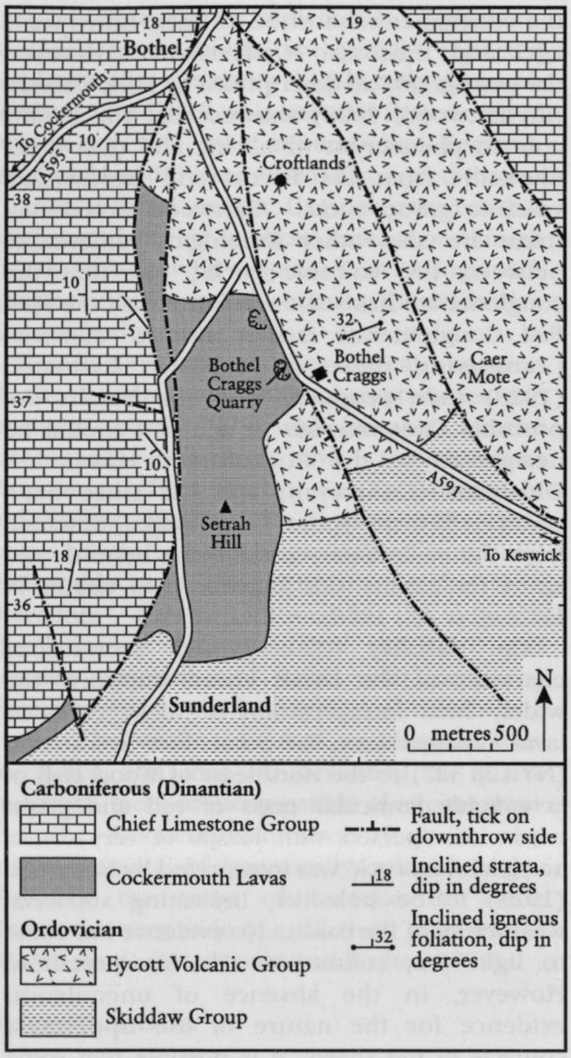

Figure 3.5 Map of the area around the Bothel Craggs Quarry GCR site. Based on British Geological Survey 1:50 000 Sheet 23, Cockermouth (1997).

Description

The description of the Bothel Craggs Quarry GCR site is based on the published accounts by Eastwood (1928) and Eastwood *et al.* (1968), and on field maps in the archives of the British Geological Survey. Approximately 4 m of blue-black, sparsely amygdaloidal, fine-grained tholeiitic andesite are exposed in the quarry (Figure 3.6). Pseudo-columnar joints are very poorly developed and there are weak sub-horizontal joints and perhaps a faint sub-horizontal lamination. There is no evidence that more than one lava is present. Neither the top nor the base of

Figure 3.6 Bothel Craggs Quarry, excavated in fresh tholeiitic andesite of the Cockermouth Lavas; view south towards the western fells of the Lake District. (Photo: D. Stephenson.)

the Cockermouth Lavas is exposed hereabouts. The andesite is similar to that described in the **Gill Beck** GCR site report, though mineralogical alteration is ubiquitous, with albitization, carbonation and sericitization of the plagioclase, and replacement of the clinopyroxene by aggregates of carbonate and 'serpentine' (Macdonald and Walker, 1985).

Interpretation

The rock from the Bothel Craggs Quarry was described as basalt on field maps by T. Eastwood. However, despite strong alteration, an intermediate composition was determined for this rock by Macdonald and Walker (1985), who classified it as tholeiitic andesite. They also recorded tholeiitic andesite in **Gill Beck** (see GCR site report), and possibly from Ullerance Gill (NY 170 351) as an altered xenolith in basalt lava. Their paper contained the first use of the term tholeiitic andesite for any British Carboniferous lava.

The magmatic evolution of the Cockermouth Lavas, as outlined in the **Gill Beck** GCR site report, probably involved low- to medium-pressure fractional crystallization. The presence of tholeiitic andesite within the Cockermouth Lavas further suggests that high-level magma chambers were established, at least locally, enabling crystal fractionation of the parental basaltic magma to take place.

The hypersthene-normative, transitional to alkaline Dinantian volcanic rocks of the Midland Valley of Scotland, to the north, include relatively common intermediate and silicic rocks (Macdonald, 1975). In contrast, the tholeiitic lavas in Derbyshire to the south, in many respects compositionally similar to the Cockermouth Lavas, are entirely basaltic (Macdonald *et al.*, 1984). The Cockermouth Lavas are thus transitional in terms of their most evolved composition between the suites of the Midland Valley and Derbyshire.

Conclusions

Approximately 4 m of sparsely amygdaloidal, tholeiitic andesite are exposed in the Bothel Craggs Quarry GCR site. The andesite in the quarry is probably part of a single lava flow and occurs at the eastern extent of the outcrop of the Tournaisian Cockermouth Lavas. This was the first tholeiitic andesite to be recognized in a British Carboniferous lava succession and its presence suggests that high-level magma chambers were established, enabling some crystal fractionation of the basaltic parental magmas to take place. Its presence is also regionally significant among similar Dinantian rocks in Great Britain, because it shows that the Cockermouth Lavas reached a state of magmatic evolution between that seen in the Midland Valley of Scotland, where intermediate and felsic compositions are common, and that of Derbyshire, where only basic rocks occur.

LITTLE MELL FELL QUARRY, CUMBRIA (NY 429 239)

D. Millward

Introduction

A number of small, basalt intrusions and a single exposure of probable pyroclastic rocks crop out on the eastern flanks of Little Mell Fell, up to about 400 m west and north of Mellfell House (Figure 3.7). Published evidence suggests that they are related to the Dinantian Cockermouth Lavas of the north-west Lake District (Capewell, 1954; Macdonald and Walker, 1985). The igneous rocks were emplaced into cobble conglomerates of the Mell Fell Conglomerate, an alluvial-fan deposit of probable Mid- or Late Devonian age (Capewell, 1955; Wadge, 1978; Cooper *et al.*, 1993). The basalts are compositionally similar to, but are fresher than, rocks of the main outcrop of Cockermouth Lavas (see **Gill Beck** and **Bothel Craggs Quarry** GCR site reports). Thus, the intrusions represent the easternmost manifestation of this volcanic episode along the northern margin of the Lake District. Furthermore, the nearby exposure of pyroclastic rocks is the only known example of tephra deposits associated with Dinantian volcanism at the southern margin of the Solway Basin.

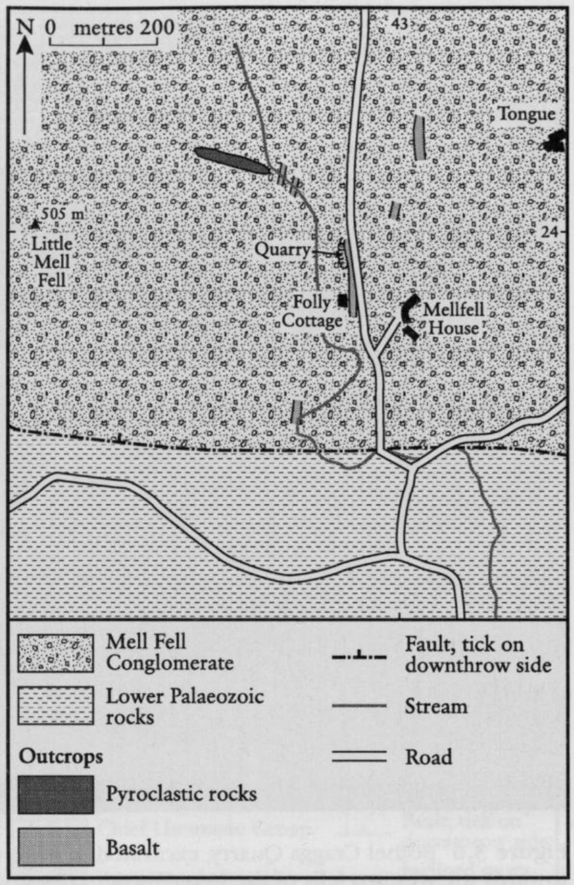

Figure 3.7 Map of the area around the Little Mell Fell Quarry GCR site. Based on British Geological Survey 1:10 000 Sheet NY 42 SW (2000).

The igneous rocks were located during the primary geological survey and described briefly in the memoir for the area (Dakyns *et al.*, 1897). Dykes near this location were mapped by Green (1918). Capewell (1954) described the Mell Fell rocks in detail, and geochemical analyses of these rocks have been interpreted by Macdonald and Walker (1985). The Little Mell Fell Quarry GCR site is included within the British Geological Survey's 1:50 000 Sheet 30, Appleby (in press).

Description

Description of these rocks is based on the accounts by Capewell (1954), and Macdonald and Walker (1985). The Little Mell Fell Quarry GCR site is the small abandoned quarry (NY 4291 2397) adjacent to the road, approximately 100 m north of Folly Cottage (Figure 3.7). Within the quarry a northerly trending basalt dyke cuts the Mell Fell Conglomerate, here composed of greywacke cobbles. The dyke forms a steep bank for about 180 m to the north of the quarry and it is further exposed immediately below the cottage; however, the dyke is not exposed in the stream 100 m south of the cottage. The width of the dyke was not recorded by Capewell (1954), but during a recent re-survey of the area the dyke width was recorded as approximately 10 m (M. McCormac, pers. comm., 1999). Capewell recorded that the western contact of the dyke dips at about 60° to the west, but that the eastern contact is irregular and nearly vertical. Trails of mainly quartz-filled vesicles are present parallel to, and 0.3–0.6 m from, the contacts. Adjacent to the dyke contacts the conglomerate matrix is slightly hardened and bleached. Towards the north end of the quarry, bleached conglomeratic rock probably represents screens of the host rock within the dyke.

Three further exposures of basalt between the road and Tongue Farm (Figure 3.7) were recorded by Capewell (1954). These may be *en échelon* segments of the dyke in the quarry or may represent at least one other separate, northerly trending dyke. At one of these exposures Capewell recorded similar contact relationships to those seen in the quarry. Other small occurrences of basalt are found in the water course approximately 300 m north-west of Mellfell House. An isolated crag of basalt 300 m south-west of Mellfell House is close to the mapped contact of the Mell Fell Conglomerate with the underlying Skiddaw Group. The geometry and contact relationships of these occurrences are not known. A NNE-trending dyke WSW of Little Mell Fell illustrated by Green (1918) could not be located by Capewell (1954), nor was it recorded during the primary geological survey.

Basalt in the Little Mell Fell Quarry is microporphyritic, with euhedral olivine and subordinate plagioclase phenocrysts. The fine-grained groundmass comprises plagioclase, augite and iron oxide. These rocks are altered, but considerably less so than the Cockermouth Lavas; olivine in particular is replaced by a chlorite-like mineral ('serpentine' according to W.W. Watts in Dakyns *et al.*, 1897; 'chlorophaeite' according to Capewell, 1954). Amygdales are of chlorite, carbonate and chalcedony. The rock exposed in the water course north-west of the quarry is a fresh sub-ophitic dolerite, in which the olivine is remarkably fresh and only serpentinized at the crystal margins.

Geochemical analyses of two rocks from this area were presented by Macdonald and Walker (1985). In common with the Cockermouth Lavas, the basalts at Little Mell Fell are tholeiitic; one of the samples is quartz-normative, the other is just olivine-normative. The Mell Fell basalts have incompatible element concentrations that are at the higher end of the compositional range encountered in the Cockermouth Lavas, suggesting that they represent some of the more enriched rocks in this formation. Macdonald and Walker (1985) expressed little doubt that the Mell Fell rocks are similar to the Cockermouth Lavas and considered them to be part of this volcanic episode.

An exposure of highly porous, greenish, unbedded lapilli-tuff, identified first by Capewell (1954), is located on the eastern slopes of Little Mell Fell approximately on the 400 m contour and 140 m ENE of the summit. The marked colour difference with the Mell Fell Conglomerate is readily noticeable. However, the contact relationship between the lapilli-tuff and the conglomerate is seen nowhere. Sub-horizontally bedded conglomerate is exposed nearby, and Capewell (1954) interpreted a steep margin to the pyroclastic rock. He also noted seepages at the base of the crags and inferred that the lapilli-tuff is underlain by impermeable basalt, either a plug or one of the north–south dykes at the base of the slope.

The lapilli-tuff comprises sub-angular clasts, mainly cobbles and pebbles of country rock, but also with glassy basaltic lapilli and blocks (Figure 3.8). Some clasts of the probable juvenile material appear to have been fused together while they were still plastic. In thin section the smaller clasts and sand-grade grains also include greywacke, siltstone and slaty mudstone. Capewell (1954) noted that parts of the rock are apparently cemented by palagonite.

Interpretation

The basalt in the quarry at Little Mell Fell was interpreted as an intrusion during the primary survey of the area (Dakyns *et al.*, 1897). The pyroclastic rocks were described first by Capewell (1954), who suggested that, because of their close proximity to the dyke-like masses of basalt, they belong to a single volcanic episode. It is also possible that these are the sub-surface remains of a single volcano. Capewell considered that, although a pipe-like

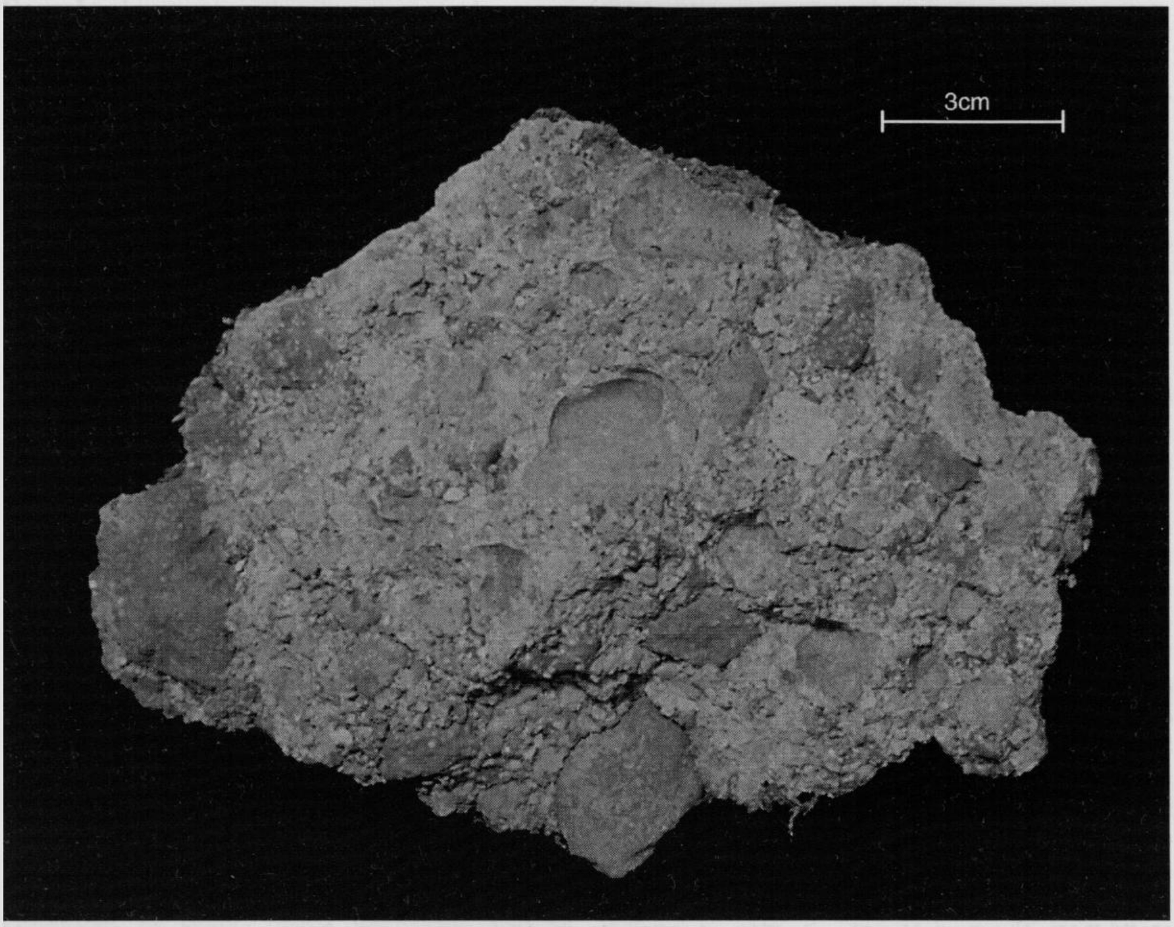

Figure 3.8 Lapilli-tuff from an inferred volcanic vent, possibly related to the Cockermouth Lavas, exposed on the hillside above the Little Mell Fell Quarry GCR site. (Photo: British Geological Survey, No. P505644, reproduced with the permission of the director, British Geological Survey, © NERC.)

geometry for the lapilli-tuff was far from certain from the field evidence, the pyroclastic rocks are likely to infill a vent conduit. The substantial amounts of country-rock pyroclasts and the presence of plastic, juvenile tephra in the lapilli-tuff clearly suggest a phreatomagmatic mode of emplacement. No other occurrences are known of pyroclastic rocks associated with the Early Carboniferous volcanism on the southern side of the Solway Basin.

Some uncertainty surrounds the age of the volcanic rocks at Little Mell Fell because there is no biostratigraphical control and no radiometric ages of these rocks have been determined. Intrusion into the probable Middle or Upper Devonian Mell Fell Conglomerate gives a maximum age, but a minimum age is not discernible from the geological relationships. Ward (in Dakyns *et al.*, 1897) considered these and other basalts in the area to be associated with the Late Carboniferous Whin Sill magmatism. Wadge *et al.* (1972) proposed a similar correlation for some olivine-dolerite dykes cutting the Eycott Volcanic Group near Melmerby in the northern part of the Cross Fell inlier. However, Capewell (1954) thought the association of olivine basalt with the quartz-dolerite sills unlikely on petrological grounds. He considered the few other occurrences of olivine-bearing basalt in the north-west of England and concluded that the best association for the Little Mell Fell rocks was with the Cockermouth Lavas. Thus, he concluded that the dykes and pyroclastic rocks were Early Carboniferous in age and that these occurrences can be regarded as an outlier of the southern Scottish Early Carboniferous volcanism. This conclusion gained further support from Macdonald and Walker (1985), who demonstrated the geochemical similarity of the Little Mell Fell Quarry rocks with the Cockermouth Lavas.

The nearest outcrop of the Cockermouth Lavas lies some 27 km to the WNW of Little Mell Fell Quarry. No similar rocks have been encountered in the intervening ground, though the base of the Carboniferous strata is well exposed. Furthermore, no dykes of similar affinity have been reported within the Lower Palaeozoic strata, an observation commented on long ago by Green (1918). However, the geochemical analyses of the dykes at Little Mell Fell confirm the earlier suggestion by Capewell (1954) that Dinantian volcanism did occur on the Lake District Block, some distance from the defined margin of the Solway Basin. Just to the north of Little Mell Fell lies the ENE-trending Causey Pike Fault (Chadwick *et al.*, 1995, fig. 3). This structure is of major importance in the development of the Lower Palaeozoic rocks of the Lake District Block (Cooper *et al.*, 1988) and is probably linked at depth to the major crustal shear zone that was re-activated during Carboniferous extension to form the Solway Basin (Chadwick *et al.*, 1995). Re-activation of the Causey Pike Fault may have provided the necessary channel for magma to reach the surface.

Conclusions

Northerly trending, near-vertical dykes of tholeiitic olivine-microphyric basalt and dolerite intrude the Devonian (Old Red Sandstone) Mell Fell Conglomerate in a quarry on the eastern flanks of Little Mell Fell and nearby. Though the dykes occur some 27 km ESE of the Cockermouth Lavas they are considered to be the easternmost manifestation of this volcanism, and thus of Tournaisian age. Some of the mafic rocks on Little Mell Fell are fresh compared with the Cockermouth Lavas. A small outcrop of unbedded lapilli-tuff, comprising pyroclasts of basalt and country rock, is considered to be the remains of an infilled vent conduit and is the only recorded occurrence of pyroclastic rocks within the Lower Carboniferous rocks of the southern margin of the Solway Basin. The volcanic rocks at Little Mell Fell are located within the Lake District Block, and the nearby Causey Pike Fault may have acted as a channel.

LANGHOLM–NEWCASTLETON HILLS, DUMFRIES AND GALLOWAY and SCOTTISH BORDERS (NY 423 901–NY 452 940)

I.T. Williamson

Introduction

The earliest phase of volcanic activity in the Northumberland, Solway and Tweed basins is probably Courceyan (early Tournaisian) in age and occurs stratigraphically at the base of the Lower Border Group, where it is represented by both the Birrenswark Volcanic Formation and the Kelso Lavas (see **Lintmill Railway Cutting** GCR site report) (Figure 3.2). Other than a minor occurrence of basaltic lava and tuff at Craiglockhart Hill in Edinburgh, these are also the earliest known examples of Dinantian volcanism within the Carboniferous–Permian Igneous Province of northern Britain.

The Langholm–Newcastleton Hills GCR site is located approximately 7 km north-east and 5 km north-west of the towns of Langholm and Newcastleton respectively. It exposes a representative section through the Birrenswark Volcanic Formation, consisting of up to 90 m of basaltic lavas with thin intercalations of reddened siltstone and sandstone. The formation extends from Annandale eastward for about 22.5 km, to the north of Newcastleton, and takes its name from exposures on Birrenswark Hill (NY 185 787), several kilometres to the west of the GCR site. However, as the level of exposure and range of lithologies and structures there are comparatively poor, this site has been selected in preference (Figure 3.9).

Though these volcanic rocks received passing mention in Teall (1888) and Geikie (1897), they were referred to as contemporaneous 'porphyrites' of Early Carboniferous age on the one-inch scale primary geological map of the area (Langholm, Sheet 11, 1883), and described as the 'volcanic rocks of Tarras Water and Birrenswark' by Peach and Horne (1903). McRobert (1920) outlined the distribution and nature of these rocks, and fuller accounts, particularly of the petrography, were given by Pallister (1952) and Elliott (1960). Details of the Birrenswark Volcanic Formation were included in the Geological Survey memoir (Lumsden *et al.*, 1967). Leeder (1974) discussed the lavas in some detail in relation to

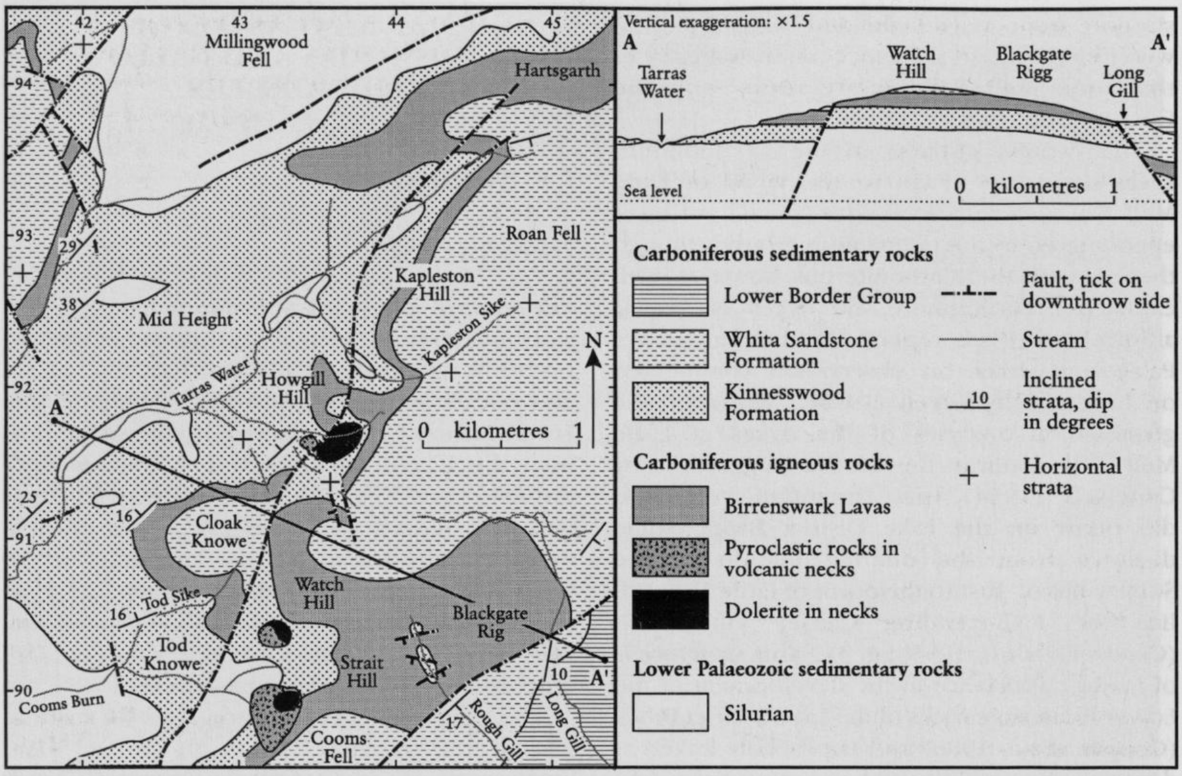

Figure 3.9 Map and cross-section of the area around the Langholm–Newcastleton Hills GCR site. Based on Geological Survey 1:63 360 Sheet 11, Langholm (1968).

the origin and overall development of the Early Carboniferous sedimentary basins. More recently, the petrology and geochemistry of these rocks have contributed to wider-ranging studies of the genesis of magmas in this tectonic setting by Macdonald (1975) and Smedley (1986a,b, 1988a).

Description

The Langholm–Newcastleton Hills is a poorly defined area of upland situated between Eskdale and Liddesdale in the foothills of the Southern Uplands. The area covered by the GCR site contains peaty moorland and rough hill grazing with incised river valleys and erosional gullies on the principal escarpment. The Birrenswark Volcanic Formation forms a persistent bench-like feature along the scarp slopes on the eastern side of the valley of the Tarras Water (Figure 3.10).

In the GCR site, the Birrenswark Volcanic Formation overlies Upper Old Red Sandstone (ORS) facies rocks unconformably, though elsewhere the volcanic rocks rest directly on basement rocks of Silurian (Wenlock) greywackes, siltstones and mudstones. The ORS facies sequence, now designated the Kinnesswood Formation, is dominated by red, cross-bedded sandstones, but a distinctive compact, light-grey-brown, calcareous sandstone overlain by 1.2 m of red calcareous mudstones, immediately underlies the lavas in Kapleston Sike (NY 4409 9203). Similar sandstone beds are also present below the base of the lavas in the Tod Sike section at NY 4284 9061. These rocks are believed to have been deposited as fluvial sediments in a hot and semi-arid environment (Leeder, 1971, 1974). The basalts are succeeded by a sequence of predominantly fine- to medium-grained arenaceous strata that is over 300 m thick in the Langholm district, where it is known as the 'Whita Sandstone Formation' (Nairn, 1956, 1958; Lumsden *et al.*, 1967). Conglomerates within the lower parts of this sequence contain basalt clasts.

In the Langholm–Newcastleton Hills the Birrenswark Volcanic Formation comprises a sequence of olivine basalts and hawaiites, with a maximum composite thickness of just over 61 m

Figure 3.10 View from the bank of the Tarras Water, towards the slopes of Cloak Knowe in the Langholm–Newcastleton Hills GCR site. Lavas of the Birrenswark Volcanic Formation form the distinct feature with scattered exposures midway up the slope; the lower slopes are till covered, and river terraces occupy the foreground. (Photo: K.M. Goodenough.)

(Lumsden *et al.*, 1967). However, Leeder (1974) has demonstrated considerable variation over the whole outcrop: the basalts may be up to 90 m thick but are absent locally west of Langholm. Individual basalt sheets, interpreted as lava, are generally less than 30 m thick and may be massive, amygdaloidal or glassy. Many parts are vesicular and vein breccias are a characteristic feature of some flows. Thin reddened carapaces occur on some lavas and, rarely, lateritic palaeosols are developed on the upper surfaces. Sedimentary intercalations of reddened siltstone and sandstone are present locally. Most exposures are extremely weathered, and spheroidal weathering is common.

The better sections through the formation were described by Lumsden *et al.* (1967). Three of these, at Tod Sike (NY 4294 9070), Howgill Hill (NY 4365 9190) and Hartsgarth Fell (NY 4470 9350), fall within the GCR site (Figure 3.9).

Tod Sike

In Tod Sike, on the south side of Cloak Knowe, there is intermittent exposure of 24.4 m of highly weathered basaltic lavas. There are probably several lavas or lava-flow units present, perhaps up to seven, though the tops and bases of these are often difficult to distinguish. Only two flows can be identified with any confidence. These are an olivine-microphyric basalt with a few scattered feldspar phenocrysts ('Dalmeny' type of MacGregor, 1928) that occurs at the base, and a glassy, macroporphyritic olivine basalt with phenocrysts of both feldspar and olivine ('Markle' type) that occurs higher in the sequence. Lumsden *et al.* (1967) recorded the presence of a single thin sedimentary intercalation some 18.3 m above the base of the section, but did not give further lithological details.

Howgill Hill and Kapleston Sike

A 22 m-thick complete section through the Birrenswark Volcanic Formation is exposed in the stream section of Kapleston Sike on the north-eastern side of Howgill Hill (Figure 3.9). Four lavas are present, ranging in thickness from 3.66 m to 7.32 m. All are deeply weathered and red-stained, amygdaloidal olivine-microphyric basalts ('Dalmeny' type), but the middle two flows may be distinguished by their glassy and compact nature. A thin sedimentary unit comprising 1.5 m of red silty sandstone separates the top two lavas.

Around Howgill Hill the basal lava forms a strong, readily mapped feature. The flow forming this feature is a highly weathered olivine- and feldspar-microphyric basalt ('Jedburgh' type) which does not appear to be represented in the Kapleston Sike section.

Hartsgarth Fell

North of Kapleston Sike the lavas crop out along Kapleston Hill and extend into the deep valley at the head of the Tarras Water under Hartsgarth Fell. There are several excellent sections here and the formation is about 29 m thick. The basal flow is a 7.6 m-thick, coarse-grained, olivine-clinopyroxene-plagioclase-macrophyric basalt ('Dunsapie' type). As elsewhere, the rest of the succession is dominated by olivine-microphyric basalts ('Dalmeny' type), some of them glassy, and at least three flows have been identified. A thin sandstone unit up to 0.6 m thick, overlies the lowest 'Dalmeny'-type flow.

Although the sections described above are relatively close to one another, exact correlation between them is difficult. For example, the different types of lava at the base of each section clearly demonstrate a considerable degree of overstep of various early flows by later olivine-microporphyritic types. Sections around Watch Hill (NY 436 908) also show this contrast in basal flow types.

Numerous volcanic necks and attendant intrusions are associated geographically with the more easterly outcrops of the Birrenswark Volcanic Formation. They cut Lower Carboniferous strata up to the level of the Glencartholm Volcanic Beds (see **River Esk, Glencartholm** GCR site report) and so it is clear that many have no possible connection with the Birrenswark Volcanic Formation. However, it has been suggested that the large Strait Hill–Cooms Fell Neck (NY 433 899) may have been one of several in the near vicinity that erupted the basalts of the Birrenswark Volcanic Formation (McRobert, 1920; Elliott, 1960; Lumsden *et al.*, 1967; Figure 3.9). Here, pyroclastic breccia, in an outcrop approximately 350 m by 400 m, is intruded by a small plug of olivine-augite-microphyric basalt that does not match any of the lavas within the GCR site. Other examples within the GCR site occur on the south-west flank of Watch Hill (NY 433 904) and to the south of Howgill Hill (NY 436 916). The necks mainly comprise unbedded basaltic tuff and pyroclastic breccia containing clasts of igneous rock, especially much decomposed basaltic glass and olivine basalt; there is also a variable proportion of sedimentary rock debris. The intrusions are usually plug-like bodies of basalt or dolerite that are compositionally similar to the lavas. The Howgill Sike Plug, which intrudes the Howgill Hill Neck, is larger than that of Strait Hill. It is a porphyritic basalt with zoned, partially resorbed phenocrysts of plagioclase and corroded phenocrysts of augite and olivine. Orthopyroxene and spinel are rare components of both the Strait Hill and Howgill Sike plugs, though it is unclear whether these are partially resorbed high-pressure phenocrysts, or xenocrysts, derived from disaggregating lherzolite inclusions carried in the magma from deep crustal levels (Upton, 1982).

The basalts of the Birrenswark Volcanic Formation provide some of the best data on the earliest Dinantian phase of volcanic activity in northern Britain. Earlier field-orientated studies suggested that they are entirely basaltic. However, Smedley (1986a) referred to the lavas of the Birrenswark Volcanic Formation collectively as transitional basalt and hawaiite, and the sequence on Kirk Hill (NY 462 864) some 6 km to the south-east of the GCR site comprises mainly basaltic hawaiites and hawaiites. More evolved compositions have not been reported from the GCR site, but mugearite occurs elsewhere, for example at Middlebie Burn (NY 216 767) near Birrenswark. Both Macdonald (1975) and Smedley (1986a) have shown that the basalts of the Birrenswark Volcanic Formation, being relatively low in alkalis and predominantly hypersthene ± quartz-normative, are among the most transitional to tholeiitic of all the Dinantian volcanic sequences in northern Britain; only the Cockermouth Lavas are more tholeiitic. However, Smedley (1986a) also found that some of the basalts of the Birrenswark Volcanic Formation are nepheline-normative.

Interpretation

Eruption of the Birrenswark Volcanic Formation probably occurred during Tournaisian times, though the biostratigraphical evidence for this is far from certain (e.g. Elliott, 1960; Lumsden *et al.*, 1967; Chadwick *et al.*, 1995). A contrary view was put forward by Nairn (1956) who, in his study of the Lower Carboniferous rocks west of the River Esk, considered that the base of the

Carboniferous System should be placed at the base of the sedimentary rocks overlying the Birrenswark Volcanic Formation. The Upper Old Red Sandstone facies rocks conformably underlying the volcanic rocks were formerly regarded as Late Devonian, but are now considered to be of Tournaisian age (Lumsden *et al.*, 1967; Day, 1970; Leeder, 1971). The succeeding sedimentary rocks are known to be younger than earliest Tournaisian age.

All of the lavas appear to have been erupted in a subaerial environment and there is no record of either pillow lavas or the development of hyaloclastites. Pahoehoe structures have not been seen and most lavas are probably aa type; some show reddened oxidized tops and possible lateritic palaeosols (boles). Sedimentary interbeds up to 10 m thick show that the volcanism was often punctuated by long periods of quiescence that allowed the establishment of localized fluvial and lacustrine systems. The number, thickness and composition of the lavas in any one section vary over comparatively short distances. This probably indicates that most of the lavas were small in volume, originating from a series of small volcanoes or fissures rather than from one large composite fissure system, in contrast to the extensive flood-basalts of the Clyde Plateau Volcanic Formation, for example (see Chapter 2). The overall form of the lava field appears therefore to be one of a shallow-dipping plateau that was constructed as a series of overlapping flows of restricted lateral extent.

The basalts of the Birrenswark Volcanic Formation are considered to be penecontemporaneous with the Kelso Lavas that crop out farther to the north-east (e.g. Eckford and Ritchie, 1939), but were almost certainly erupted as a geographically separate lava field. Nairn (1956) noted thinning to both the east and west from the type locality at Birrenswark. The conclusion of Lumsden *et al.* (1967) that the volcanic formation in the area east of Tarras Water, which includes the Langholm–Newcastleton Hills GCR site, does not thin significantly in any direction, has subsequently been shown to be incorrect. The most significant advance in our understanding of the palaeogeography of these times was made by Leeder (1971, 1974). He demonstrated, using isopachytes, that the volcanic formation thins overall to the north and north-east (Leeder, 1974). He also concluded that the succession thins south-west, but evidence for this is indirect and is based on thinning south-westwards of the later Glencartholm Volcanic Beds into the Bewcastle anticline.

Leeder (1974) considered three hypotheses to explain the pattern of isopachytes. First, the current distribution could be the erosional remnants of a larger volcanic field of unknown extent. He thought this unlikely because of the conformable relationship between the lavas and overlying sedimentary rocks, and because basalt pebbles in the basal sedimentary rocks above the lavas are only present locally. His second hypothesis involved eruption from a line of fissures orientated along the line of maximum thickness. Though he considered this to be attractive, there is little support from the distribution of the volcanic necks, many of which are some distance from the maximum lava thickness. The third, and most likely, hypothesis is a relationship between the geometry of the lava pile and the pre-existing Upper Old Red Sandstone facies sedimentary basin, which is known to have had a south-west–north-east orientation (Leeder, 1974, fig. 4). Locally, within the basin, the lavas are absent and this may have been due to the presence of a palaeohigh. Leeder (1971) also concluded that emplacement of the lava field had a profound effect on sediment distribution in the area: prior to the eruptions the mean sediment transport direction was north-eastwards, but subsequently this changed to south-eastwards. However, such a change may be related more to the initiation of the Northumberland, Solway and Tweed basins and thus a change in basin geometry.

On a regional scale, the Birrenswark Volcanic Formation lavas are quite localized along the northern margins of the Northumberland and Solway basins, and are an integral part of the early basin development. According to some (e.g. Leeder, 1974), they probably do not extend far into the sub-surface beneath the basins, and Chadwick *et al.* (1995), in considering the seismic reflection data of Kimbell *et al.* (1989), pointed out that although there may be lavas at the base of the sequence elsewhere in the basins, there is no proof of this. A time interval of unknown duration is implied between emplacement of the last lava of the Birrenswark Volcanic Formation and deposition of the fluvio-deltaic sandstones of the Whita Sandstone Formation. As deposition of such thick sequences of strata requires the creation of considerable 'accommodation space', a significant degree of basin subsidence is implied, following the volcanism.

Conclusions

The Langholm–Newcastleton Hills GCR site is representative of the Tournaisian Birrenswark Volcanic Formation, a lava succession consisting of up to 90 m of basalt, basaltic hawaiite, hawaiite and rare mugearite. The GCR site neatly demonstrates many of the key features of the formation, including evidence for the structure of the lava field, form of flows, details of the rock-types present and the variations in local successions. Associated volcanic necks of tuff and pyroclastic breccia, intruded by basalt plugs, may have been the sites of eruption for some of the lavas. The conformable stratigraphical relationships with sedimentary strata above and below the lavas are particularly clear.

The lavas of the Birrenswark Volcanic Formation are an important feature of the Early Carboniferous development of the Northumberland and Solway basins and are among the earliest manifestations of volcanic activity within the Carboniferous–Permian Igneous Province of northern Britain. Their position in space and time clearly illustrates the close association of basic volcanism with the early phases of development of sedimentary basins. They have formed an integral part of petrological and geochemical studies of the igneous province and will continue to provide an important source of material for any such studies in the future.

LINTMILL RAILWAY CUTTING, SCOTTISH BORDERS (NT 727 463–NT 736 466)

I.T. Williamson

Introduction

The Lintmill Railway Cutting GCR site has been selected to represent the basaltic to hawaiitic Kelso Lavas of the Tweed Basin. These early Dinantian volcanic rocks, along with the broadly coeval, but geographically separated, Birrenswark Volcanic Formation and Cockermouth Lavas in the Solway Basin to the south-west, are important to the understanding of crustal development during the early phase of the tectonic and sedimentary evolution of the Northumberland, Solway and Tweed basins (see also **Langholm–Newcastleton Hills**, **Gill Beck** and **Bothel Craggs Quarry** GCR site reports).

The Lintmill Railway Cutting GCR site is located some 3 km east of the small town of Greenlaw, at the northern end of the arcuate outcrop of the Kelso Lavas (Figure 3.1). Here, the volcanic rocks are exposed over a distance of about 600 m within the old railway cutting and along the banks of the Blackadder Water, west of Lintmill Bridge (Figures 3.11 and 3.12); elsewhere, exposure of the Kelso Lavas is only sporadic.

The Kelso Lavas attracted some interest during the early days of Scottish geology. The well-exposed parts of these igneous rocks were first mapped by Milne (1837) and the synclinal form of the outcrop was traced by Nicol (1847). The Geological Survey six-inch to one-mile map of the Kelso area was made by J. Geikie and published on the scale of one-inch to one-mile in 1879 (Sheet 25). No memoir for the area has been published, and as yet there has been no published re-survey. Brief references to the Kelso Lavas have subsequently been made by

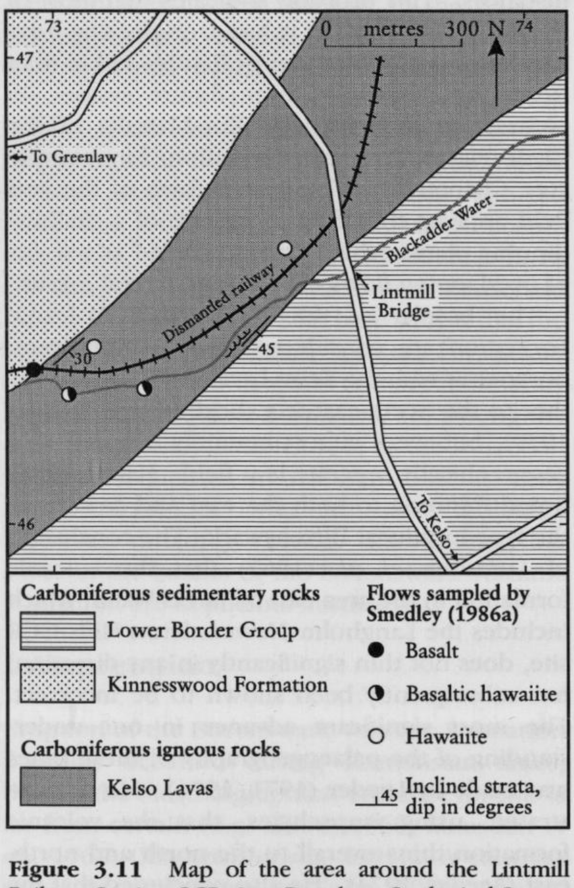

Figure 3.11 Map of the area around the Lintmill Railway Cutting GCR site. Based on Geological Survey Old Series 1:63 360 Sheet 25, Galashiels (1879); geochemical sample points from Smedley (1986a).

Figure 3.12 View east along the Lintmill Railway Cutting, with the Kelso Lavas exposed in the cutting on the left. (Photo: I.T. Williamson.)

J. Geikie (1893), A. Geikie (1897) and Goodchild (1904), but the main descriptions of the rocks are by Eckford and Ritchie (1939) and Tomkeieff (1945, 1953). More recently, the geochemistry of the Kelso Lavas has formed part of major petrogenetic studies of the Dinantian volcanic rocks of northern Britain by Macdonald (1975) and Smedley (1986a,b, 1988a).

Description

The Kelso Lavas comprise up to 12 basic and intermediate flows in their maximum development to the south of the Lintmill area (Tomkeieff, 1953), but there is little information on thickness variations over their outcrop. In the Lintmill Railway Cutting GCR site a 120 m-thick sequence of volcanic rocks rests unconformably upon sandstones of Upper Old Red Sandstone facies, and comprises perhaps six or seven lavas, interbedded with breccias, sparse thin volcaniclastic sedimentary units and possibly some thin palaeosols (see stratigraphical section below). The volcanic sequence within the site dips towards the south-east, with dips of individual units varying from 15° up to about 40°, but averaging about 25°. The top part of the sequence is not seen within the site, though nearby to the east in the Blackadder Water there are exposures of younger sedimentary rocks, dipping to the south-east at 4°–7°. The composite stratigraphical section, described from top to bottom, is described below.

	Thickness (m)
Sandstone and pebbly coarse sandstone seen 3–4 m above uppermost lava; contact not seen	
Basalt, feldspar-phyric, deeply weathered	*c.* 4
Basalt, feldspar-phyric, greenish-grey, amygdaloidal, weathered	*c.* 5
Hawaiite or basaltic hawaiite, showing crude columnar jointing and platy joints inclined at 45°–50° to the south-east, weathered; exposed in crags along the river, but not exposed in the cutting	*c.* 20
Basalts, olivine- and olivine-feldspar-phyric, interbedded massive, scoriaceous and amygdaloidal facies; localized thin, reddish-brown tuffs and/or volcaniclastic siltstone, some beds with palaeosol development; dip in cutting is 30°–40°; some calcite mineralization	*c.* 33
Basalt, predominantly massive, sporadic and irregularly developed amygdaloidal facies; feldspar phenocrysts rare and widely scattered	*c.* 12
No exposure	*c.* 12
Basalt or basaltic hawaiite, massive, fine grained, rare feldspar phenocrysts; thin amygdaloidal basal facies; crude prismatic jointing inclined to the north-west at 70°–80°	*c.* 8
Basalt or dolerite, massive; may represent a thin sill intruded along base of overlying flow	*c.* 5
Sandstone, tuffaceous, fine grained to medium grained, reddish-brown; thin lenticular unit	*c.* 1
Basalt and locally basaltic hawaiite, olivine-phyric; flow jointed in part; undulating sharp base	
Sandstones, medium grained, red and reddish-brown with some red-grey to pale-buff mottling, cross-bedded; dip about 30° to the south-east or ESE (Upper Old Red Sandstone facies)	?

Some of the lavas are probably aa flows, in which massive and rubbly or scoriaceous facies are well developed. However, the middle parts of the sequence comprise a number of individual flow units, a characteristic of pahoehoe lavas. Most of the rocks are altered and weathered with mafic phenocrysts typically replaced by iddingsite, chlorite and calcite. Brecciation and calcite veining is conspicuous locally. Tomkeieff (1953) recognized a two-fold petrographical division within the Kelso Lavas: a lower group of dominantly feldspar-phyric rocks and an upper group with clinopyroxene and/or olivine phenocrysts. The Kelso Lavas include basalt, basaltic hawaiite and hawaiite; all are hypersthene-normative and a few also have quartz in the norm, and hence they are tholeiitic (Smedley, 1986a). These rocks have remarkably similar geochemistry to the Birrenswark Volcanic Formation, but are enriched in most elements relative to the Cockermouth Lavas (Smedley, 1988a).

Interpretation

The Kelso Lavas overlie Upper Old Red Sandstone facies rocks (Kinnesswood Formation) that are thought to have been deposited on a hot semi-arid alluvial floodplain by a system of interior drainage (Leeder, 1974). The sedimentary rocks are very early Carboniferous in age and the lavas are thought to be Tournaisian, probably Courceyan (Lumsden *et al.*, 1967; George *et al.*, 1976; House *et al.*, 1977). The lavas are therefore thought to be contemporaneous with the Birrenswark Volcanic Formation and the Cockermouth Lavas.

There is no major linear dyke-swarm associated with the volcanism though small dykes and sills occur locally. The lavas are therefore presumed to have been erupted from a series of small volcanic vents (Eckford and Ritchie, 1939). More than 50 such centres are scattered over a distance of about 16 km from Langholm to Duns. They are exposed at various levels of erosion so that some appear wholly or partially filled by plugs (see **Hareheugh Craigs** and **Langholm–Newcastleton Hills** GCR site reports), or by tuff and pyroclastic breccia.

The similarity in rock-types of the Kelso Lavas and Birrenswark Volcanic Formation and the abundance of volcanic necks between the outcrops led Francis (1967) to suggest that the outcrops were once continuous. However, by constructing isopachytes for the Birrenswark lava field, Leeder (1974) demonstrated convincingly that the two most likely developed as separate though coeval fields. He also suggested that their original extent was little more than that occupied by the lavas today.

Macdonald (1975) and Smedley (1986a) demonstrated the overall similarity in geochemistry between the Kelso Lavas, the Birrenswark Volcanic Formation and the Cockermouth Lavas. However, the volcanic rocks from the Scottish Borders are considerably more enriched in minor and trace elements than those from the southern margin of the basins (Smedley, 1988a). The tholeiitic Kelso Lavas were shown clearly to be part of the mildly alkaline to tholeiitic suite that is characteristic of the Early Carboniferous volcanism in southern Scotland and northern England.

Conclusions

The Lintmill Railway Cutting GCR site is representative of the Kelso Lavas (see also **Hareheugh Craigs** GCR site report), a localized basaltic to hawaiitic lava field up to 120 m thick that was emplaced on the northern flank of the Tweed Basin during Early Carboniferous (Tournaisian, possibly Courceyan) times. The site provides a good section through six or seven basalt, basaltic hawaiite and hawaiite lavas with sparse intercalated volcaniclastic sedimentary rocks. The volcanic rocks are tholeiitic and are the products of magmatic events induced by crustal extension associated with the early evolution of the Tweed Basin. They provide vital information for the understanding of this development and also enable comparative studies with other Dinantian volcanic rocks from elsewhere within the Carboniferous–Permian Igneous Province of northern Britain.

HAREHEUGH CRAIGS, SCOTTISH BORDERS (NT 688 401)

I.T. Williamson

Introduction

The Hareheugh Craigs GCR site has been selected because it contains a particularly good example of a plug-like composite intrusion of basaltic hawaiite to hawaiite composition, associated with the early Dinantian Kelso Lavas in the Tweed Basin, which are represented by the **Lintmill Railway Cutting** GCR site.

Hareheugh Craigs is a craggy hilltop about 2.5 km north-west of the village of Stichill and close to the town of Kelso (Figures 3.13 and 3.14). The 1879 Geological Survey one-inch map shows an intrusive body of 'felstone' within the Kelso Lavas and the underlying Upper Old Red Sandstone strata. The revision survey concluded that this intrusion is probably a plug (Fowler and MacGregor, 1938). The petrography of the intrusion has been described in several papers on the igneous rocks of the Kelso area (Eckford and Ritchie, 1939; Tomkeieff, 1945, 1953) and it has been included in geochemical studies of Dinantian magmatism in northern Britain by Macdonald (1975) and Smedley (1986a).

Description

The Hareheugh Craigs intrusion cuts the Kelso Lavas, which are exposed intermittently in the immediately surrounding area and are represented by the nearby **Lintmill Railway Cutting** GCR site. The intrusion has a diameter of up to about 600 m and comprises two lithologically contrasting facies, one above the other. The best section through the lower part of the intrusion is seen in a former road-metal quarry (NT 6880 3990). Though partially obscured by waste tipping and natural degradation, the lower parts of the 20 m-high, main face of the quarry expose a beautifully fresh, feldspar-macrophyric basaltic hawaiite or hawaiite, with dark, lustrous feldspars having a tendency to weather-out on rock faces. The feldspars are irregularly distributed giving a diffusely banded or layered appearance of alternating porphyritic and aphyric zones. The upper parts of the face show a coarser-grained, though less porphyritic, or aphyric basaltic hawaiite or hawaiite. The highest exposures in the quarry and those on adjacent hillsides are of the upper facies. This comprises large phenocrysts of olivine, clinopyroxene and spinel in addition to plagioclase in a fine-grained groundmass. The junction between the two types is poorly exposed, but appears to be regular with only a thin zone of transition and no obvious cooling of one facies against the other.

Columnar cooling joints are up to 1.75 m across and are inclined radially outwards at up to 70°. A number of calcite-filled vugs occur, and thin, irregular veins cut the intrusion. The presence of shear zones with some slickensides and veining probably indicates faulting.

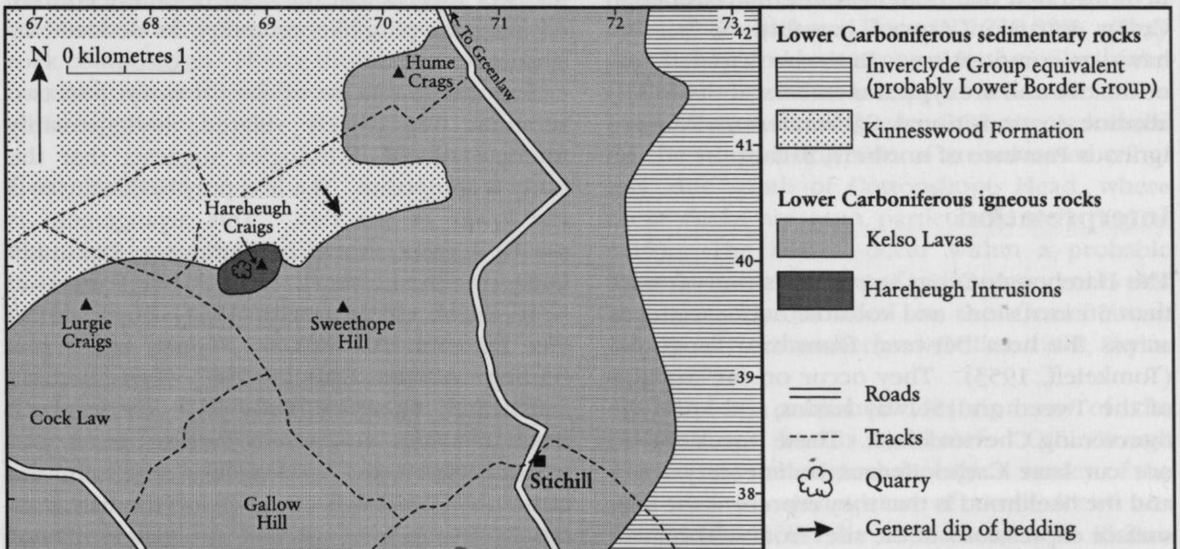

Figure 3.13 Map of the area around the Hareheugh Craigs GCR site. Based on Geological Survey Old Series 1:63 360 Sheet 25, Galashiels (1879).

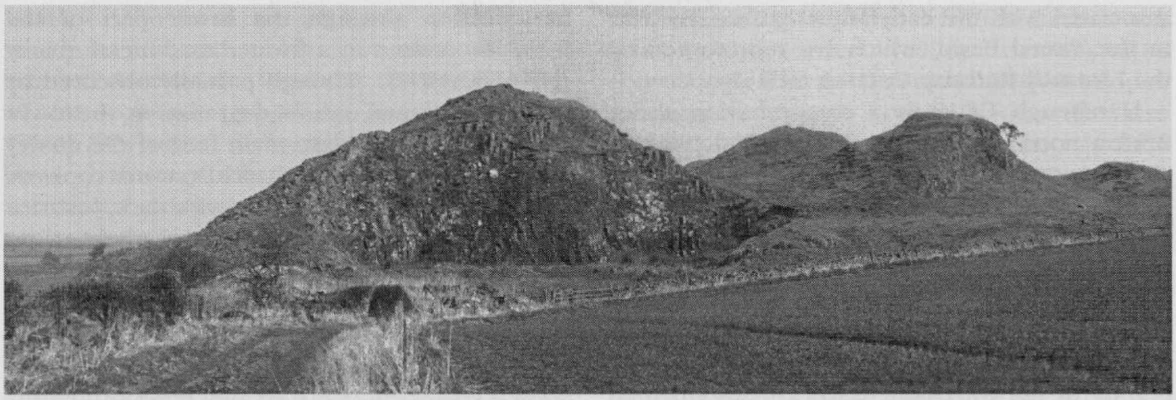

Figure 3.14 View from the south-west of Hareheugh Craigs; a plug-like intrusion of hawaiitic rocks within the Kelso Lavas. (Photo: C. MacFadyen.)

Eckford and Ritchie (1939) described the intrusion as a 'Markle' (or related) basalt in the local classification scheme of MacGregor (1928); that is, an olivine basalt with feldspar phenocrysts, and ophitic augite forming part of a coarse-grained groundmass. Tomkeieff (1945) described the quarry exposures as olivine dolerite with patches and bands of 'Markle'-type basalt, and classed the exposures on the upper part of the hill as 'Dunsapie'-type basalt. In his later paper he referred to the intrusion as a composite plug of 'Markle' type (Tomkeieff, 1953). However, both Macdonald (1975) and Smedley (1986a) demonstrated that both facies of the Hareheugh Craigs intrusion are of hawaiite or basaltic hawaiite composition. Both are hypersthene-normative and are typical members of the mildly alkaline to transitional Carboniferous–Permian Igneous Province of northern Britain.

Interpretation

The Hareheugh Craigs intrusion is one of more than 50 intrusions and volcanic necks scattered across the area between Duns and Langholm (Tomkeieff, 1953). They occur on the margins of the Tweed and Solway basins and span the intervening Cheviot Block. These intrusions do not cut later Carboniferous sedimentary rocks and the likelihood is that they represent the subsurface expressions of the sites from which most of the Dinantian volcanic rocks (Birrenswark Volcanic Formation, Kershopefoot basalts and Kelso Lavas) of the district were erupted. Some may have fed younger flows that have been subsequently lost through erosion. There is no evidence, in the form of linear dyke-swarms for example, for major fissure eruption, though some of these volcanic 'centres' define crude lineaments. The Hareheugh Craigs intrusion is one of several forming a NE-trending lineament from Hume (NT 710 420) towards Smailholm (NT 640 350) (Tomkeieff, 1953, fig. 1).

At Hareheugh Craigs, basaltic hawaiites and hawaiites are intruded into the generally more basic Kelso Lavas. Contact relationships are not entirely clear. There is some suggestion of systematic variations in grain size across the margins of the intrusion and some evidence for the presence of steeply inclined contacts. These features suggest that the body does indeed have an irregular plug-like geometry, as deduced by previous surveyors.

The differentiation of the intrusion into two separate but closely related, and possibly intergradational, lithologies suggests that the body is composite. The less porphyritic facies is the lower of the two. This arrangement is similar to that shown by composite Dinantian lavas from the Clyde Plateau Volcanic Formation near Greenock (Kennedy, 1931; Boyd, 1974) (see **Dunrod Hill** GCR site report) and in the Stirling area (MacDonald, 1967; Francis *et al.*, 1970) (see **Campsie Fells** GCR site report). Several other composite bodies from the province are listed by Macdonald (1975), the closest to Hareheugh Craigs being the hawaiite–basalt association exposed on Lurgie Craigs some 1.3 km to the west.

The compositions of the two facies indicate a degree of differentiation of the original magma from alkali olivine basalt to hawaiite, probably through the mechanism of crystal fractionation at relatively high pressures (Macdonald, 1975).

It is unlikely that such differentiation occurred *in situ* at the levels seen today in the Hareheugh Craigs intrusion. Rather, the emplacement may have resulted from a series of closely spaced, pulsed evacuations of a deeper level, internally stratified or zoned magma chamber, in which there was a downward gradation from more to less differentiated material. Another possibility is that fractionation took place during slow ascent of the magma and that this led to the postulated vertical zonation. Both mechanisms could lead to the internal intrusive arrangements seen today.

In general, where relative ages of emplacement can be deduced in such composite bodies, the more evolved aphyric or microporphyritic component is intruded before the less evolved macroporphyritic one. This is probably because, due to crystal-settling mechanisms, most phenocrysts are concentrated in the lower parts of the underlying magma chamber, and this crystal-charged batch of magma is usually the last to be either erupted or intruded at shallower crustal levels. It is significant that the porphyritic facies includes plagioclase in addition to mafic phenocrysts, suggesting that the magma at this level was already somewhat fractionated and hence of lower density that a basaltic magma, allowing the plagioclase to sink. At Hareheugh Craigs, the relative ages of the two facies are not known and the few available analyses suggest little correlation between the phenocryst content and whole-rock composition. Hence the exact sequence of fractionation and emplacement remains somewhat enigmatic.

Conclusions

The intrusion at the Hareheugh Craigs GCR site is representative of the many small plug-like intrusions that cut the Tournaisian Kelso Lavas and forms part of a swarm of over 50 sub-volcanic necks extending south-westwards into the Birrenswark Volcanic Formation. These may have been the sites of eruption of the lavas. It is one of few intrusions in the swarm that are composite. The two components present are basaltic hawaiite or hawaiite in composition; the lower one is generally aphyric to sparsely porphyritic, but the upper component contains large phenocrysts of feldspar, olivine, clinopyroxene and spinel.

The components of the composite intrusion are considered to have been emplaced as two magmas of differing composition that formed within a single, vertically zoned magma column at deeper levels in the Earth's crust. Such composite bodies, whether in the form of lava flows or intrusions, provide a valuable insight into the crystallization and chemical evolution of magmas as they rise through the crust (see **Dunrod Hill** GCR site report). The fresh rocks of this intrusion have contributed to several important petrographical and geochemical studies of the igneous rocks associated with the early development of the Tweed, Northumberland and Solway basins.

COTTONSHOPE HEAD QUARRY, NORTHUMBERLAND (NT 803 058)

D. Millward

Introduction

A thin succession of tholeiitic, olivine-phyric basalts, referred to as the 'Cottonshope lavas' or 'Cottonshope basalts', is the only exposed record of effusive volcanic activity associated with development of the Northumberland Basin in Early Carboniferous times. The lavas crop out in a handful of localities south-west of the Cheviot Block, including Spithope Burn (NT 760 050), Hungry Law (NT 747 062), and between the Baseinghope Burn (NT 700 045) and the Chattlehope Burn (NT 730 028). They are thickest and best exposed in the valley of the Cottonshope Burn, in Upper Redesdale. The Cottonshope Head Quarry GCR site is located on the north-facing side of an unnamed tributary, due south of Cottonshope Head, where these rocks are seen particularly well (Figure 3.15). The basalts occur within a probable Tournaisian succession of sedimentary rocks that are currently included in the Cementstone Group of Northumberland (Miller, 1887; Taylor *et al.*, 1971).

The few published descriptions of the Cottonshope basalts are brief. C.T. Clough carried out the original geological survey of the area and his description of these rocks was incorporated in the Otterburn and Elsdon memoir (Miller, 1887). The succession and petrography were described later by Tomkeieff (1931). The area including the GCR site was re-mapped in 1932 by W. Anderson and is included in the Geological Survey Sheet 8 (1951). Previous work was summarized by Randall (1995a).

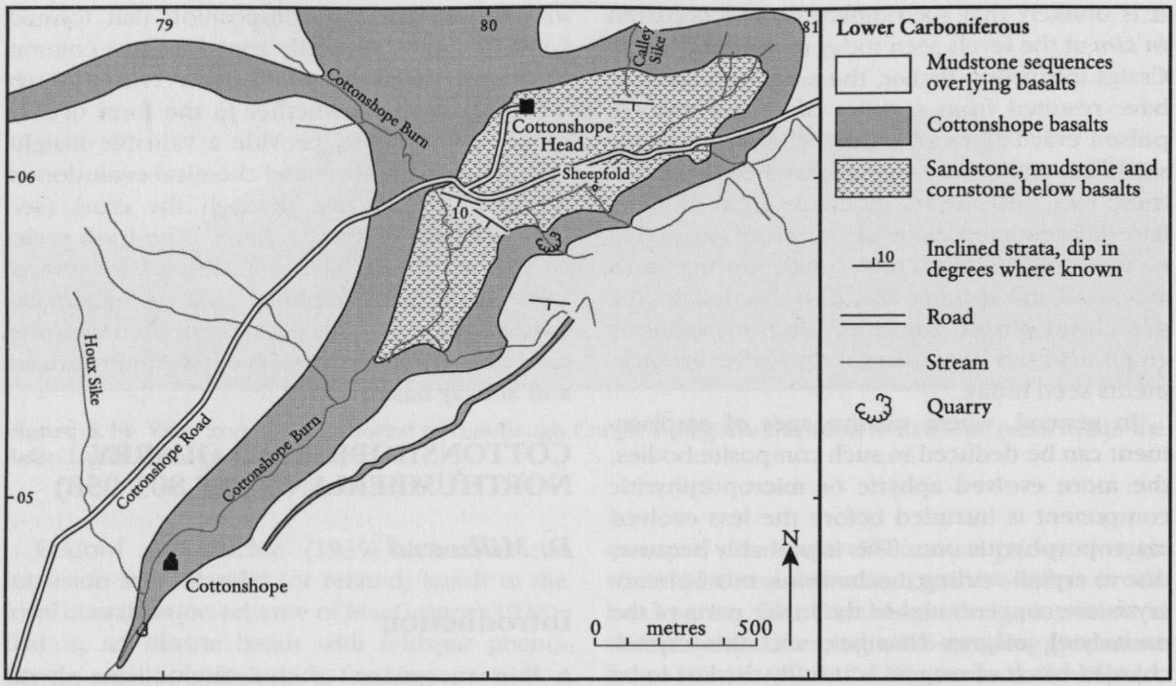

Figure 3.15 Map of the area around the Cottonshope Head Quarry GCR site. Based on geological mapping by W. Anderson (1932, Geological Survey Archives).

Description

The description of the Cottonshope Head Quarry GCR site is based on the published accounts and on field maps and manuscript notes in the British Geological Survey archives; this is supplemented by recent observations.

The upper part of the Cottonshope valley provides a complete section through the relatively poorly exposed Cottonshope basalts (Figure 3.15). Lower Carboniferous strata there dip at about 10° to the SSW or south. The succession underlying the basalts is dominated by red or grey flaggy sandstones with brown ochreous spotting, along with interbedded purple, red, lilac and green mudstones containing ochreous concretions. Thin beds of concretionary carbonate ('cornstone') were noted during a visit to the site in 2000. These strata were called the 'Lower Freestone Beds' by Miller (1887) and Taylor *et al*. (1971), but the presence of the 'cornstones' is a diagnostic feature of the Kinnesswood Formation of central Scotland. In places, grey mudstone is exposed just beneath the basalts and a prominent spring line occurs along the junction. The volcanic rocks are overlain by dark-grey and greenish mudstones with sandstones and thin 'cementstones'.

The volcanic succession comprises three sheets of basalt. The lowest one is 12 m thick and has an undulating pillow-like to slaggy, scoriaceous top in which there are sedimentary infills. This is overlain directly by vesicular basalt, 6 m thick. The uppermost basalt is also 6 m thick, but is separated from the underlying ones by 6 m of bedded mudstones, flaggy sandstones and 'cementstones'. In the Spithope Burn (NT 767 057), 3 km west of the GCR site, these beds contain fragments of basalt. The lowest two basalt sheets are exposed in a small road-metal quarry within the GCR site (Figure 3.15). The section exposed there in 1946 is recorded in manuscript notes in the British Geological Survey archives as follows:

'Upper lava: lava, dark grey with a few small vesicles 10 feet [3 m].
Vesicular lava with inclusions of shale and cementstones up to 2 × 1 feet in size, 1 to 10 feet [0.3–3 m].
Junction between lavas slightly undulating.
Lower lava: vesicular lava, coloured. The amygdales are filled with quartz and calcite, lined with green earth (chlorite) 3 feet [0.9 m].
Grey lava, apparently similar to top lava 8 feet [2.4 m].'

Miller (1887) described the inclusions of sedimentary rock recorded from the upper unit as having been bleached and altered by heat. The base of the upper unit was poorly exposed at the rear of the quarry in the summer of 2000, adjacent to a small stream. There, unbedded carbonate rock appeared to contain scattered angular fragments of basalt.

Though the volcanic rocks are generally conformable with the sedimentary rocks, Miller (1887) noted possible irregularity at the base of the lowest basalt in a stream about 800 m south of Cottonshope Head, probably at about NT 799 054. There, the base of the basalt cuts down at least 20 cm into the underlying 'cementstone' bed.

Generally, the basalt is closely fractured and considerably altered, though fresher material is noted from Calley Sike (NT 804 064), 600 m NNE of the quarry. The rock has been described by Tomkeieff (1931), as a typical 'Dalmeny'-type basalt, according to the classification of MacGregor (1928). It is a grey microporphyritic basalt containing phenocrysts of olivine, plagioclase and augite. There are numerous subhedral pseudomorphs of 'serpentine', iddingsite, chlorite and calcite after olivine phenocrysts. The groundmass comprises altered feldspar laths with intergranular chloritized augite and iron oxide. The major element composition of the lowest basalt in the succession, collected a little downstream from the GCR site at NT 7959 0537, is given by Tomkeieff (1931). Recalculation of this analysis shows the rock to be hypersthene- and very slightly quartz-normative.

The manuscript notes also record that the southern face of the quarry is formed by an easterly trending vein of quartz and galena about 80 mm wide. This is one of two similarly orientated veins, the second of which is exposed in Cottonshope Burn, 250 m downstream from Cottonshope (NT 7891 0456).

Interpretation

The Cottonshope basalts were interpreted as subaqueous by Miller (1887) and as submarine by Taylor *et al*. (1971). However, the presence of 'cornstones' in the sequence below the lavas suggests a subaerial environment. 'Cornstones' form as a result of a fluctuating water table through the soils of semi-arid floodplains. The 'cementstone' succession interbedded with, and overlying, the lavas is also thought to have been deposited on a fluvial coastal plain with lagoons (Taylor *et al*., 1971).

Miller (1887) considered that the inclusions of sedimentary rock seen in the basalts were caught up in the moving flow and that some of the larger masses of sandstone represent the filling of an irregular topography during the intervals between eruptions. However, the undulating and pillow-like form to the top of each basalt was thought by Tomkeieff (1931) to resemble the hummocky and ropy surface of subaerial pahoehoe lava, though similar surface features are now known to be characteristic of submarine sheet-flows. He also concluded that fragments of sediment within the lava, and clasts of basalt within the sedimentary rocks overlying the second unit at Spithope, indicate that the basalts and sediments were contemporaneous, and hence imply an extrusive origin.

The three basalt lavas preserved in the Cottonshope Burn outcrop make this the thickest and best development of the Cottonshope basalts. Elsewhere, only one lava is thought to be present. Tomkeieff (1931) speculated on the source of the lavas. On Carter Fell (NT 680 060), a basalt plug and associated mushroom-like sill cut through a lenticular bed of agglomerate, rising into the lower part of the Fell Sandstone Group above the Cementstone Group. Though this basalt is clearly later than the Cottonshope basalts, Tomkeieff thought it possible that, as the agglomerate rests directly on the Lower Freestones, it could have been the site of an active volcano at the earlier time.

The Cottonshope basalts, which lie only about 100 m beneath the top of the Cementstone Group in Redesdale, have been tentatively assigned an early Tournaisian age. This is not well constrained because of the restricted nature of the fossils in the enclosing sedimentary rocks (Taylor *et al*., 1971). The Cementstone Group of Northumberland probably correlates with the Lower Border Group farther west, and the top of the latter corresponds approximately to the Tournaisian–Visean boundary.

The recent discovery of 'cornstones' within the Lower Freestone Beds provides significant new evidence for eruption of the Cottonshope basalts during early Tournaisian times. M.A.E. Browne (pers. comm., 2000) examined the succession in Cottonshope Burn and concluded that the lithofacies present are typical of the Kinnesswood Formation of central Scotland. In the New Cumnock area (NS 6670 2158) this formation has been found to contain miospores of earliest Tournaisian age (LN–PC biozones) (Turner, 1994). This would place the volcanism at approximately the same time as the Birrenswark Volcanic Formation and the Kelso Lavas. Though the geochemical composition of the Cottonshope basalts is known only from a single major-element analysis, this suggests that these rocks are probably little different from the transitional, tholeiitic to mildly alkaline rocks that constitute the other early Dinantian volcanic rocks of northern England.

Conclusions

The Cottonshope Head Quarry GCR site is representative of the Cottonshope basalts, the only exposed sequence of Early Carboniferous volcanic rocks within the Northumberland Basin. The volcanic succession crops out southwest of the Cheviot Block and comprises up to three intensely altered, massive to highly amygdaloidal and scoriaceous, basalt lavas. The lavas are intercalated with sedimentary rocks of the Cementstone Group of Northumberland and overlie a sequence of sandstone, mudstone and concretionary carbonate ('cornstone') that was deposited on a semi-arid floodplain. The sedimentary rocks below the lavas were formerly assigned to the Lower Freestone Beds, a local formation, but they may be correlated with the Kinnesswood Formation of central Scotland. The age of the latter suggests that the Cottonshope basalts are early Tournaisian in age and hence they are part of the Birrenswark–Kelso volcanic episode.

KERSHOPE BRIDGE, SCOTTISH BORDERS (NY 496 833–NY 501 835)

I.T. Williamson

Introduction

The Kershope Bridge GCR site has been selected to represent the Kershopefoot basalts, a sequence of basaltic rocks that occurs within the upper part of the (Holkerian) Middle Border Group in a number of places south and southeast of Langholm. The site includes the disused road-metal quarry at Kershope Bridge and a section in the nearby Kershope Burn that here forms the border between Scotland and England (Figure 3.16). There are several other small,

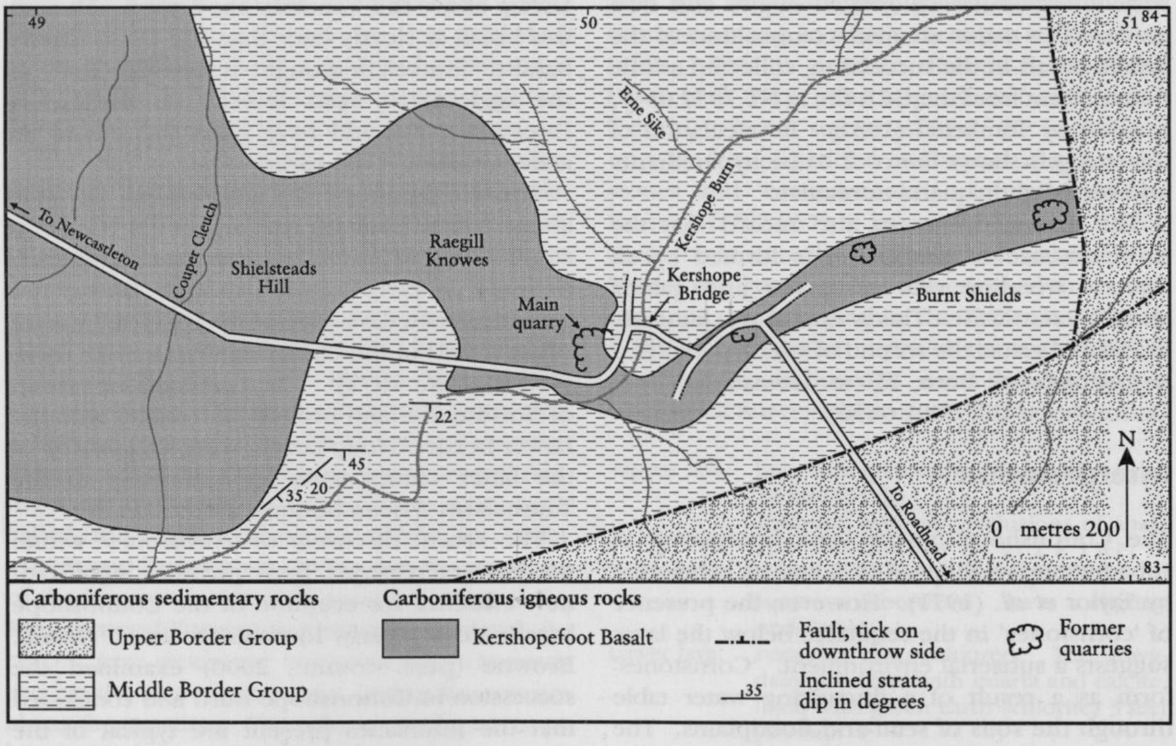

Figure 3.16 Map of the area around the Kershope Bridge GCR site. Based on Geological Survey 1:63 360 Sheet 11, Langholm (1968).

disconnected outcrops in the area, mostly on the Scottish side of the border to the west and north-east. These rocks represent a phase of tholeiitic to mildly alkaline volcanic activity younger than that of the Kelso Lavas, the Birrenswark Volcanic Formation and the Cockermouth basalts but older than the Glencartholm Volcanic Beds. All of these are associated with the early tectonic and sedimentary evolution of the Northumberland, Solway and Tweed basins.

The various exposures of the Kershopefoot basalts occupy more-or-less the same stratigraphical position throughout their outcrop. They attain a maximum thickness of about 36.5 m and probably represent several lava flows. Doubt has been expressed about their extrusive origin. Peach and Horne (1903) believed that some of the outcrops of the Kershopefoot basalts are lavas whereas others are intrusions. Garwood (1931), Lumsden *et al.* (1967) and Day (1970) referred to these rocks non-committally as the 'Kershopefoot Basalt'. Detailed descriptions of the rocks are to be found in Geological Survey memoirs (Lumsden *et al.*, 1967; Day, 1970) and the basalts were included in a widespread geochemical study of Dinantian magmatism in northern Britain by Smedley (1986a).

Description

The Kershopefoot basalts occur within the Middle Border Group, part of the Carboniferous Limestone Series. Possibly up to 490 m thick, the group shows an overall upward transition from mudstones and limestones with marine faunas and algal bands, through alternating, thinly bedded siltstones, sandstones, calcareous siltstones and limestones, to a massive, current-bedded sandstone unit known as the Larriston Sandstone. However, according to Lumsden *et al.* (1967), this sandstone facies cannot be traced confidently south of Newcastleton into the region occupied by the Kershopefoot basalts. Here, the sequence in the Kershope Burn shows sandstones with many more interbeds of argillaceous and calcareous units (Day, 1970). Beds below the basalts, exposed on neighbouring hillsides, comprise yellow, cross-bedded, fine-grained sandstone.

Basaltic lava is well exposed in the quarry by Kershope Bridge (NY 5005 8339). Neither the top nor the bottom contact of the basalt is seen in the area, but Lumsden *et al.* (1967) reported sedimentary rocks in the floor of the quarry. The quarry faces reveal a bluish- to greenish-grey fine- to medium-grained basalt with unevenly distributed, large feldspar phenocrysts (typically 5–6 mm). These are rare to absent towards the base and top of the section. The main mass of the rock is neither vesicular nor amygdaloidal, though there are scattered large drusy cavities with infillings and coatings of carbonate, quartz in various forms, and baryte. The higher parts of the exposed section are much more vesicular and brecciated with some scoriaceous fragments. Long-exposed surfaces show the development of spheroidal weathering. The worked faces are cut by jointing with well-developed near-vertical to steeply inclined NE-(prominent) and SW-directed sets.

In the Kershope Burn, downstream (south-westwards) from the bridge, there are exposures of basalt and associated sedimentary rocks. The burn crosses the axes of two synclines with the result that beds are repeated. The amygdaloidal basalt is weathered greenish-brown, and shows some signs of brecciation. In the more north-eastern exposures (NY 4973 8332), it is overlain by massive sandstone and limestone dipping to the south-west though the contact is not seen. The upper parts of the basalt are also seen a little farther to the south-west at NY 4941 8310. Here amygdales are filled with red and green clay and may be flattened and streaked out, parallel to a faint flow-induced igneous lamination. The basalt is overlain by limestones, cherty sandstone breccia and sandstones dipping to the south-east, but here also, the contact relationships are not seen. Dips are typically in the range 20° to 45°.

Comprehensive descriptions of the petrography of the Kershopefoot basalts were given by R.W. Elliot (in Lumsden *et al.*, 1967) and R.K. Harrison (in Day, 1970). In thin section they show some lateral variation. At Kershope Bridge the rock is a porphyritic olivine basalt with phenocrysts of abundant labradorite, and subordinate olivine and clinopyroxene. The groundmass consists of labradorite laths, commonly strongly flow-banded and ophitically enveloped by anhedral to subhedral, purplish titaniferous augite. At other localities the groundmass clinopyroxene of the basalt may be colourless and either microlitic or skeletal. Minor constituents include titaniferous magnetite, ilmenite, orthopyroxene and apatite. There is also a little interstitial analcime. Vesicles are infilled by chlorite, calcite, baryte, quartz, chalcedony and agate; amethystine quartz has been reported from low levels within the mass.

Whole-rock analyses show that the rocks range from basalt to hawaiite, with a range of silica saturation from hypersthene-normative to slightly nepheline-normative (Smedley, 1986a). As such they are typical of the transitional tholeiitic to mildly alkaline Dinantian lavas of northern Britain.

A yellow-weathered silty dolostone in the Kershope Burn (NY 4974 8332), about 0.6 m above the top of the basalt, is intensely brecciated, with veins of ankerite and joint surfaces coated with bitumen. There are also patches of chlorite, scattered grains of pyrite and the rock has been partially recrystallized. These features have been explained as a diagenetic rather than a contact metamorphic phenomena (Day, 1970).

Interpretation

On the first edition of the one-inch Geological Survey map (Sheet 11, Scotland; 1883), the western outcrops of the Kershopefoot basalts were shown as intrusive, whereas the others, including the outcrop of which the Kershope Bridge GCR site is part, were regarded as lava. Peach and Horne (1903) included the Kershope Bridge to Carby Hill outcrop as lavas within the Glencartholm Volcanic Beds. Elliott (1960) also considered some of the western outcrops of the Kershopefoot basalts to be intrusive, though the outcrop at Kershope Bridge was outside his area of study. Uncertainties over the mode of emplacement of these rocks were also expressed by Lumsden *et al.* (1967) and Day (1970), though eruption as lavas was suggested because of the slaggy vesicular upper part of the sequence. However, these authors agreed that the various outcrops are part of the same mass at a single stratigraphical level, and are at least 60 m (Day, 1970) or 120 m (Lumsden *et al.*, 1967) beneath the Glencartholm Volcanic Beds.

The doubt as to whether the Kershopefoot basalts are extrusive or intrusive arises because no contacts are exposed. There is a general lack of post-depositional recrystallization of the adjacent strata, but there are some thermal effects. At the base of the basalt in the Kershope Burn there is a general induration and some subtle bleaching of the more argillaceous beds. This is typical of both lavas and shallow intrusions but is not diagnostic. The upper contact is potentially more informative and, in Kershope Quarry, the uppermost parts of the basalt show well-developed vesiculation and brecciation, both phenomena more typical of, but not exclusive to, extrusive rocks. The basalt here is considered to be most probably a lava and, though inconclusive, the weight of evidence suggests that the basalts in general are extrusive rather than intrusive, and hence are contemporaneous with sedimentation in the Middle Border Group. Although no interflow junctions are known, the overall thickness of the basalts (over 36 m) and the variation in petrography and geochemistry between the various outcrops suggest the presence of more than one flow.

In terms of major-and trace-element compositions the Kershopefoot basalts are similar to the older lavas of the Birrenswark Volcanic Formation, which crop out in the same area (Smedley, 1986a, 1988a). However, there are notable differences in some incompatible trace-element ratios that have been attributed to the derivation of magmas from a different portion of the mantle, despite the close geographical proximity and the relatively short time interval between the two volcanic episodes.

Conclusions

The Kershope Bridge GCR site is representative of the Kershopefoot basalts, a localized extrusive event during the deposition of the Visean Middle Border Group. Olivine-clinopyroxene-plagioclase-phyric basalt, basaltic hawaiite and hawaiite comprise a succession up to 36.5 m thick. Though commonly interpreted as lava, there is some doubt about this and an intrusive emplacement is possible. Like the younger Glencartholm Volcanic Beds and the older Kelso Lavas and Birrenswark Volcanic Formation, the activity that produced the basalts seen at Kershope Bridge is thought to relate to tensional fracturing along the northern margin of the actively subsiding Northumberland and Solway basins. This site provides important evidence within this framework for continued stretching and crustal thinning, allowing intermittent eruption of basaltic magmas during the development of Early Carboniferous basins.

RIVER ESK, GLENCARTHOLM, DUMFRIES AND GALLOWAY (NY 377 792–NY 376 799)

I.T. Williamson

Introduction

The River Esk at Glencartholm, some 5 km south of Langholm, is the type locality of the Glencartholm Volcanic Beds (Figure 3.17). These are the only preserved record of significant pyroclastic activity associated with development of the Northumberland, Solway and Tweed basins. Also, these beds are the youngest of three chronologically distinct volcanic episodes within the Dinantian succession of the Langholm area (Figure 3.2; the other two are the Birrenswark Volcanic Formation and the Kershopefoot basalts; see **Langholm–Newcastleton Hills** and **Kershope Bridge** GCR site reports). All of these volcanic successions are critical to our understanding of Late Palaeozoic crustal and mantle processes, during the development of the Northumberland, Solway and Tweed basins. The Glencartholm Volcanic Beds were formed during the later part of the syn-extensional phase (Chadwick *et al.*, 1995).

The Glencartholm Volcanic Beds comprise a 150–180 m-thick sequence of tuffs, localized lavas and interbedded mudstone and sandstone (many of which are volcaniclastic) and thin limestones, that occurs at the base of the (Visean) Upper Border Group. Palaeontological data from the interbedded lithologies suggest an age close to the Holkerian–Asbian boundary (George *et al.*, 1976).

Brief accounts of the volcanic beds were included in publications by Peach and Horne (1903), Barrett and Richey (1945), Elliott (1960), Lumsden and Wilson (1961) and Leeder (1974); the most comprehensive description, including the type locality, is that of Lumsden *et al.* (1967).

Glencartholm has been credited as being the richest fossil fish site within the Carboniferous rocks of the British Isles, and in an international context is one of the most important Palaeozoic vertebrate sites in the world (see Dineley and Metcalf, 1999). It is also an important palaeobotanical site (see Cleal and Thomas, 1995).

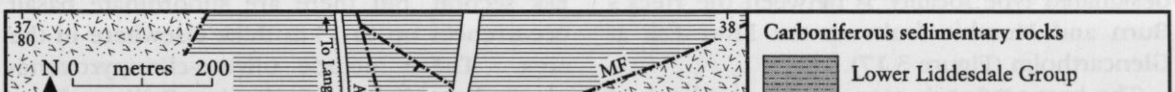

Figure 3.18 Map of the area around the River Esk, Glencartholm GCR site. (HBF = Heck's Burn Fault; MF = Mumbie Fault.) Based on Geological Survey 1:10 560 Sheet NY 37 NE (1967).

Description

The Glencartholm Volcanic Beds are the basal unit of the Upper Border Group, a succession mainly composed of sedimentary rocks and in total probably up to 800 m thick. The group may be divided into a lower unit comprising the volcanic rocks, marine mudstones, limestones and subordinate sandstones and coals, and an overlying upper unit dominated by arenaceous rocks with only subordinate argillaceous strata and thin limestones. These, and equivalent strata of early Asbian age, are known to crop out widely in the western and central parts of the Northumberland Basin, and along the northern margins of the Solway Basin.

The Glencartholm Volcanic Beds form a disconnected series of narrow outcrops extending over a distance of about 10 km from the Irvine Burn north-eastwards to the Muir Burn. Owing to the relatively soft and easily weathered nature of these fragmental volcanic rocks, there are few exposures other than in stream sections. The most extensive sections are found in Haw Gill, Pow Gill and Rae Gill, all streams at the head of the Muir Burn, but the best known, and the designated type locality, is between the Heck's Burn and Mumbie faults in the River Esk at Glencartholm (Figure 3.17).

The best section is seen on the east bank of the River Esk. Here, the strata dip mainly towards the south or SSE at 5° to 60°, but the section is complicated by numerous small faults and folds. The lowest beds, at least 21 m thick, are poorly bedded blue-grey tuffs with thin beds of fine- to coarse-grained volcaniclastic sandstone. Both contain altered fragments of igneous and sedimentary rock. The larger fragments in the tuffs, up to 7.5 cm across, are mostly of sandstone, quartz, chert and 'cementstone'; the igneous clasts are considerably smaller. These are succeeded by interbedded tuffs, tuffaceous sandstones and siltstones, and 'cementstones'. There are numerous thin beds of chert, cherty sandstone and limestone.

The richly fossiliferous beds that have yielded internationally important arthropods and fish, first noted by Peach and Horne (1903), are exposed over a distance of 46 m about 460 m upstream from the mouth of Heck's Burn (NY 3764 7960). They are a gently dipping sequence of fissile calcareous sandstones with thin 'cementstones', and fine-grained sandy limestone up to 15 cm thick. Beyond these beds, and across a couple of faults, there is a gently folded sequence of soft sandstones, tuffaceous sandstones and thin tuffs. Some of the tuffaceous beds display upward-fining graded bedding. The highest beds in the section are exposed upstream from the Heck's Burn Fault. These comprise thinly bedded, multicoloured, tuffaceous siltstones and silty sandstones with numerous thin 'cementstones', limestones and rare coal.

The petrography of the volcaniclastic rocks in the River Esk section has been described by R.W. Elliot (in Lumsden *et al.*, 1967). Descriptions of similar rocks in the Archerbeck Borehole (NY 4157 7815) were described by D.C. Knill (in Lumsden and Wilson, 1961). The igneous clasts in the tuffs provide clues to contemporary volcanism in the region. They include basalt, spilitic basalt, andesite, mugearite, trachyte and scoria. Other clasts include sandstone, quartz, chert and 'cementstone'. Small crystals of cassiterite have been found in samples from the borehole.

Effusive volcanic activity was not a major feature of this volcanic episode as there are few occurrences of lavas within the Glencartholm Volcanic Beds. None are noted from the River Esk section, but there are subordinate basalt occurrences up to 15 m thick elsewhere in the area. These include olivine-clinopyroxene-plagioclase-phyric basalt in Palling Burn (*c.* NT 305 788), some distance west of Glencartholm and, to the east, some very altered olivine-clinopyroxene-phyric basalts at Rae Gill (NT 4493 8240) and hawaiite or mugearite at Pow Gill (NT 4493 8289). All occur at or near the base of the volcanic sequence and, upon brecciation or erosion, may have supplied some of the clasts in the tuffs at higher levels.

Interpretation

The Glencartholm Volcanic Beds have a wide, but variable, distribution across the Northumberland and Solway basins and were proved at depth in the Archerbeck Borehole near Canonbie (Lumsden and Wilson, 1961). The Oakshawford Tuff of the Bewcastle Anticline (Day, 1970) is probably its lateral equivalent. The sequence in the Archerbeck Borehole is greater than 152 m thick, whereas only a metre of tuff at Oakshawford suggests an abrupt thinning to the south (Leeder, 1974). None of the natural sections is complete, being either faulted or poorly exposed.

The volcanic beds are predominantly of pyroclastic and volcaniclastic sedimentary origin; fine-grained crystal- and lapilli-tuffs in beds a few centimetres to over 20 m thick are typical. The thinner beds, often with upward-fining profiles, are dominated by volcanic material whereas many of the thicker units include a high proportion of non-volcanic detritus. The interbedded, commonly spectacularly fossiliferous, sedimentary rocks were interpreted by Lumsden *et al.* (1967) as lagoonal to shallow marine sequences that were buried periodically by volcanic, predominantly ash-fall, deposits. The volcanic eruptions effectively contaminated these sedimentary environments, killing off any biota for significant periods until re-colonization could take place.

Volcanic necks and associated minor intrusions in the region appear not to cut strata younger than the Glencartholm Volcanic Beds and have consequently been suggested as possible sources for the volcanic rocks (McRobert, 1920; Lumsden *et al.*, 1967). As much of the igneous detritus is compositionally distinct from the associated lavas, D.C. Knill (in Lumsden and Wilson, 1961) suggested that it may have been derived from the erosion of pre-existing volcanic rocks. However, this scenario was dismissed by Lumsden *et al.* (1967) on the grounds that similar detritus is not present in the interbedded sedimentary rocks and such rapid and repeated changes in provenance were unlikely to have occurred.

Conclusions

The section in the River Esk at Glencartholm is the type locality for the Visean Glencartholm Volcanic Beds. These predominantly bedded tuffs and volcaniclastic sedimentary rocks, in a succession 150–180 m thick, represent the latest and only significant volcaniclastic event during Dinantian volcanism associated with the early evolution of the Northumberland, Solway and Tweed basins. Fossil plant, arthropod and fish remains within the marine and lagoonal strata interbedded with these rocks are of international importance.