Carboniferous and Permian Igneous Rocks of Great Britain

North of the Variscan Front

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Chapter 6

Tholeiitic sills and dykes of Scotland and northern England

INTRODUCTION

S.C. Loughlin and D. Stephenson

The transitional to alkaline volcanism that dominated northern Britain throughout most of Carboniferous and Early Permian times (chapters 2–5) was interrupted in the Late Carboniferous by a short-lived period of tholeiitic magmatism during which basaltic magma was intruded into near-surface strata. The resulting intrusions comprise the Whin Sill-complex of northern England and the Midland Valley Sill-complex of Scotland, together with associated dykes (Figures 6.1 and 6.2). There are no associated extrusive rocks. Both sill-complexes were emplaced into major sedimentary basins and are associated with extensive ESE- to ENE-trending dyke-swarms that extend well beyond the basin limits both to the west and east. Dykes of quartz-dolerite occur in the Outer Hebrides in the west, and to the east they can be traced under the North Sea at least as far as the Central Graben (Smythe, 1994). Tholeiitic rocks of similar age in southern Scandinavia are probably related (e.g. Hjelmqvist, 1939; Weigand, 1975; Russell, 1976; Francis, 1978a,b; Russell and Smythe, 1983; Smythe *et al.*, 1995) and the intrusions are clearly part of a substantial igneous province stretching across northern Europe.

The tholeiitic intrusions of northern England and the Midland Valley played an important part in the early development of the geological sciences in Great Britain. The word 'sill' was used in northern England to describe a flat-lying layer of rock, and 'whin' meant hard. Hence the term 'Whin Sill' may have been in use long before the origin of the rock was known and is most likely the first geological use of the word 'sill' (Randall, 1995b). In the Midland Valley, the origin of sills was the subject of controversy in the early part of the 19th century when 'Huttonians' and 'Wernerians' had different views on the subject. However, neither group considered that the sills might be intrusive. After Hall (1805) had pointed out the significance of glassy selvages on dykes at Vesuvius, Allan (1812), Rhind (1836) and Cunningham (1838) all described the fine-grained upper margins of sills in the Edinburgh district and their intrusive nature was eventually accepted (e.g. Howell and Geikie, 1861). The Great Whin Sill was recognized to be of igneous origin early in the 19th century (e.g. Trevelyan, 1823), but there was debate as to whether it was an intrusive sheet (Sedgwick, 1827) or a lava flow (e.g. Phillips, 1836; Hutton, 1838). The intrusive origin was finally established through the investigations of Clough (1876) in Teesdale, and of Tate (1867, 1871) and Topley and Lebour (1877) in Northumberland, and the Great Whin Sill became regarded as the type example of a sill.

Rocks of this tholeiitic suite were some of the earliest to be studied in detail using the petrological microscope, resulting in some interpretations and descriptions of features that we now take for granted. Allport (1874) pointed out the similarities between various sills in the Midland Valley thus establishing their close relationship. He also described the presence of quartz in the quartz-dolerite sill of North Queensferry but he was of the opinion that it was a secondary mineral. Further investigation of quartz from the Stirling Sill near Denny provided some evidence for its primary nature (Geikie, 1880) and Teall (1888), investigating rocks from Ratho Quarry, near Edinburgh, for his classic work on *British Petrography*, finally established quartz as a primary constituent of the dolerites. Teall also produced the first descriptions of micropegmatite and hypersthene from the quartz-dolerites of Scotland and pointed out the petrographical similarity between the Midland Valley Sill-complex and the Whin Sill-complex. His accounts of the petrography of the Great Whin Sill and associated dykes are early classics (Teall, 1884a,b).

By the early 20th century, the sills and dykes were well established in the literature and some of the most detailed accounts date from this period (Heslop, 1908, 1912; Holmes and Harwood, 1928; Wager, 1929a,b; Tomkeieff, 1929; Smythe, 1930a; Walker, 1934, 1935). More recent specialist studies of individual intrusions, records of borehole sections and age determinations are listed in the detailed sections that follow, but it is important to note the geochemical overviews of the Scottish dykes by Macdonald *et al.* (1981), the Whin Sill-complex by Thorpe and Macdonald (1985) and the whole tholeiitic suite by Howard (1999). Several general reviews are available of the Midland Valley Sill-complex and dykes (Walker, 1965), the Whin Sill-complex and dykes (A.C. Dunham, 1970; Randall, 1995b; Johnson and K.C. Dunham, 2001) and the whole suite (A.C. Dunham and Strasser-King, 1982; Francis, 1982).

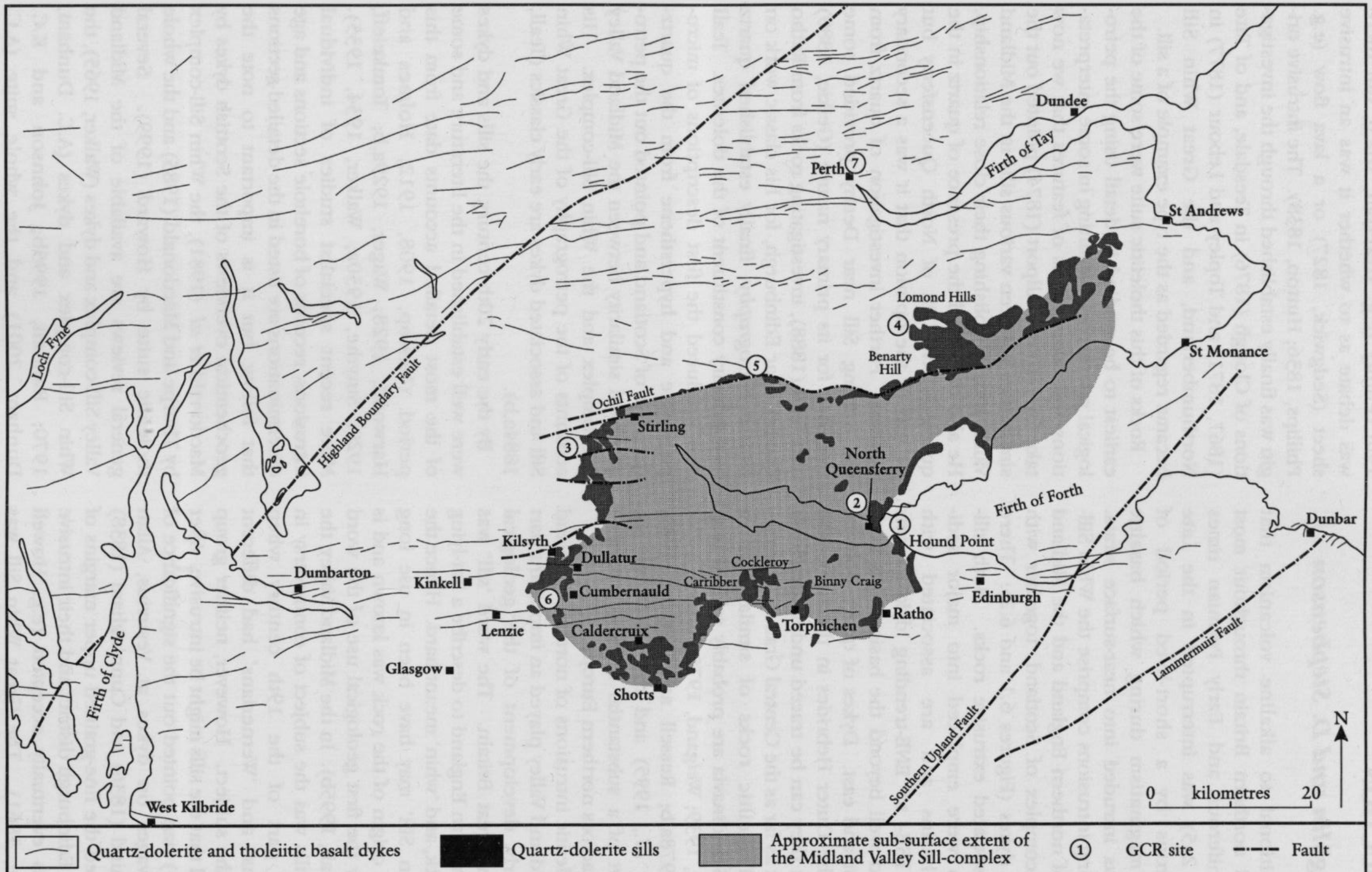

Figure 6.1 Map of the Midland Valley and southern Highlands of Scotland, showing the distribution of the Late Carboniferous tholeiitic Midland Valley Sill-complex and the associated dyke-swarm. GCR sites: 1 = South Queensferry to Hound Point (see Chapter 5); 2 = North Queensferry Road Cuttings; 3 = Wallstale; 4 = Lomond Hills; 5 = Gloom Hill, Dollar; 6 = Mollinsburn Cuttings; 7 = Corsiehill Quarry. After Cameron and Stephenson (1985).

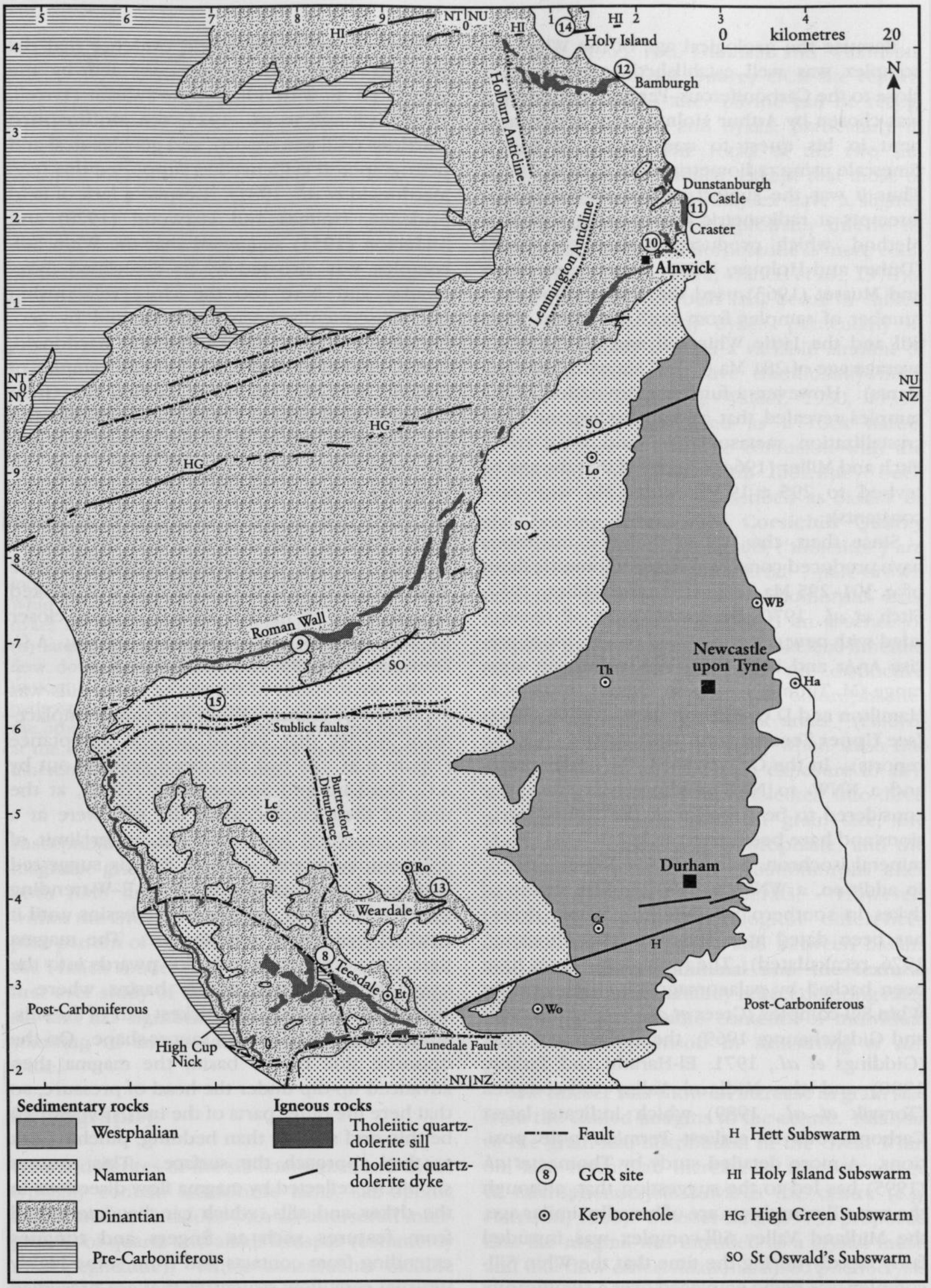

Figure 6.2 Map of north-east England, showing the area intruded by the Late Carboniferous tholeiitic Whin Sill-complex and associated dyke subswarms. GCR sites: 8 = Upper Teesdale; 9 = Steel Rigg to Sewingshields Crags; 10 = Longhoughton Quarry; 11 = Cullernose Point to Castle Point; 12 = Budle Point to Harkess Rocks; 13 = Greenfoot Quarry; 14 = Holy Island; 15 = Wydon. (Key boreholes: Cr = Crook; Et = Ettersgill; Ha = Harton; Lh = Longhorseley; Lo = Longcleugh; Ro = Rookhope; Th = Throckley; WB = Whitley Bay; Wo = Woodland.) After Francis (1982); and Johnson and K.C. Dunham (2001).

Because the geological age of the Whin Sill-complex was well established as being quite close to the Carboniferous–Permian boundary, it was chosen by Arthur Holmes as a key component in his quest to construct a geological timescale using radiometric dates (Lewis, 2001). Thus it was the subject of one of the earliest attempts at radiometric dating using a Helium Method, which produced a date of 196 Ma (Dubey and Holmes, 1929). Much later, Miller and Musset (1963) used the K-Ar method on a number of samples from both the Great Whin Sill and the Little Whin Sill and produced an average age of 281 Ma (*c.* 287 Ma with new constants). However, a further examination of the samples revealed that all had undergone post-crystallization metasomatism and as a result Fitch and Miller (1964) suggested that the age be revised to 295 ± 19 Ma (*c.* 301 Ma with new constants).

Since then, the British tholeiitic intrusions have produced consistent K-Ar radiometric dates of *c.* 301–295 Ma (e.g. Fitch and Miller, 1967; Fitch *et al.*, 1970; De Souza, 1979; all recalculated with new constants) and recent, more precise Ar-Ar and U-Pb dates are within the same range (M. Timmerman, pers. comm., 2002; M.A. Hamilton and D.G. Pearson, pers. comm., 2002) (see **Upper Teesdale** and **Holy Island** GCR site reports). In the Oslo Graben, the earliest lavas and a NNW- to NNE-trending dyke-swarm are considered to be coeval with the British intrusions and have been dated at 297 ± 9 Ma (Rb-Sr mineral isochron; Sundvoll and Larsen, 1993). In addition, a WNW- to NW-trending swarm of dykes in southern Sweden (the Scania dykes) has been dated at *c.* 300 Ma (K-Ar; Klingspor, 1976, recalculated). The radiometric dates have been backed by palaeomagnetic studies of the Whin Sill-complex (Creer *et al.*, 1959; Storetvedt and Gidskehaung, 1969), the Holy Island Dyke (Giddings *et al.*, 1971; El-Harathi and Tarling, 1988) and the Midland Valley Sill-complex (Torsvik *et al.*, 1989) which indicate latest Carboniferous to earliest Permian pole positions. A more detailed study by Thomas *et al.* (1995) has led to the suggestion that, although the two sill-complexes are of broadly similar age, the Midland Valley Sill-complex was intruded fairly rapidly during the time that the Whin Sill-complex was being emplaced over a significantly longer period. Geological evidence for the age of emplacement of each complex is discussed in the individual sections.

There is some direct field evidence that the Midland Valley Sill-complex was fed by the associated E–W-trending dyke-swarm (Tyrrell, 1909b; Clough *et al.*, 1925; see **Mollinsburn Cuttings** GCR site report), and geochemical and petrographical evidence has supported this (e.g. Macdonald *et al.*, 1981). Despite a lack of field evidence, Holmes and Harwood (1928) and Anderson (1951) suggested that the Whin Sill-complex was also fed by its associated dyke-swarm, and here too the close relationship has subsequently been demonstrated by geochemical evidence (e.g. Thorpe and Macdonald, 1985). However, there are several examples of basaltic dyke-like intrusions cutting the Great Whin Sill, and Smythe (1930a) and Johnson and K.C. Dunham (2001) cited this as evidence that the dyke-swarm was a slightly later event. In both the Midland Valley and northern England, the dykes tend to occur on the flanks of basins rather than in their centres where the sills are thickest. Hence, some authors argued that the exposed dykes were not the feeders and invoked the presence of 'hidden feeders' located closer to the thickest sills (Smythe, 1930a; A.C. Dunham, 1970; Randall, 1995b).

The relationship of the dykes to the sills was explained by Francis (1982) in a single emplacement model that gained general acceptance (Figure 6.3). As had also been pointed out by A.C. Dunham and Strasser-King (1982), at the time of their emplacement the sills were at a lower structural level than the upper limit of dyke emplacement. Hence, Francis suggested that basaltic magma rose along the E–W-trending dykes at the outer margins of the basins until it reached hydrostatic equilibrium. The magma then flowed gravitationally downwards into the lower, central parts of the basins where it accumulated to form the thickest part of the sills, which assumed an overall saucer-shape. On the opposite side of the basin, the magma then advanced up-dip under the head of pressure, so that here the outer parts of the intrusion tend to be thin and steeper than bedding, pinching out as they approach the surface. This process should be reflected by magma flow directions in the dykes and sills, which can be determined from features such as fingers and tongues extending from contacts and from some highly unusual ropy flow structures that are preserved at the **Holy Island** and **Budle Point to Harkess Rocks** GCR sites. Of more widespread use is the technique of AMS (anisotropy of magnetic

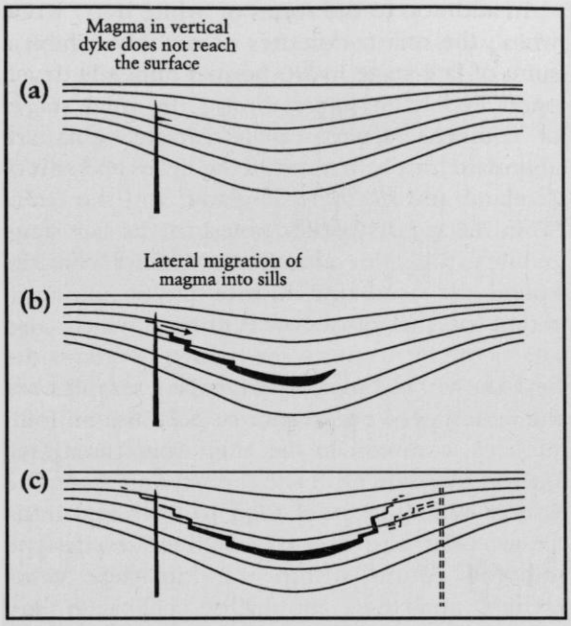

Figure 6.3 Diagram to illustrate the mechanism of intrusion of the Midland Valley Sill-complex and the Whin Sill-complex, suggested by Francis (1982). (a) dykes are intruded to 0.5–1.0 km below the surface; (b) lateral intrusion of magma leads to gravitational flow down-dip and accumulation of magma at the bottom of the sedimentary basin; (c) to achieve hydrostatic equilibrium, magma advances up-dip on the other side of the basin, with *en échelon* fingering at the leading edge. Broken lines indicate variation inherent in multiple dyke sources.

susceptibility), which measures the alignment of magnetic grains. Preliminary results, involving both AMS and macroscopic flow indicators within the Great Whin Sill, indicate a more complex pattern of magma flow than is suggested by the Francis model (Liss *et al.*, 2001). This is the first ever study of the magnetic fabric of a large sill and has significant potential for the understanding of emplacement mechanisms worldwide.

Petrography

Quartz-dolerites of the sill-complexes and dykes typically contain labradorite laths, sub-ophitic augite and Fe-Ti oxides with an intersertal intergrowth of quartz and alkali feldspar (commonly micropegmatitic). Minor constituents include hypersthene or pigeonite, hornblende, biotite, apatite and pyrite. Secondary quartz, carbonate and chlorite may occur. Fresh olivine has been found only in the Little Whin Sill (A.C. Dunham and Kaye, 1965; A.C. Dunham and Wilkinson, 1992; see **Greenfoot Quarry** GCR site report) but pseudomorphs after olivine can be recognized in many sills and dykes, particularly in chilled margins. The rocks of the two sill-complexes are very similar, except that those of the Midland Valley Sill-complex have a slightly coarser grain-size overall (probably due to its greater thickness) and hornblende is more common (Walker, 1935, 1952; Francis *et al.*, 1970).

The finer-grained rocks that occur in chilled margins and in many dykes, particularly in Scotland, usually contain a variable amount of intersertal glass and have traditionally been termed 'tholeiites' (e.g. Walker, 1930, 1935). This is no longer used as a rock name, partly because of possible confusion with the geochemical use of the term 'tholeiitic'. Such rocks are more simply described as basalts or glass-bearing basalts (see **Corsiehill Quarry** GCR site report). The basalts ('tholeiites') are characterized by intersertal pale-brown microlitic glass, sporadic pseudomorphs after olivine (e.g. Allport, 1874) and an absence of Ca-poor pyroxene. In addition, skeletal ilmenite may occur in the glass and the distinctive amorphous chloritic material 'chlorophaeite' may be present in intersertal areas (chlorophaeite is a rich green colour when fresh but rapidly oxidizes to brown on exposure to air). Walker (1935) divided the 'tholeiites' into three petrographic types based on grain size, the abundance of glass and chlorophaite, and the presence or absence of pseudomorphs after early ferromagnesian minerals. However, geochemical and mineralogical differences between the basalt types and between basalts and dolerites are minimal and the textural differences almost certainly reflect differing rates of cooling and volatile contents of individual intrusions (Stephenson in Armstrong *et al.*, 1985).

The thicker sills show an increase in grain size from the chilled margins to the centre. Analysis of the grain-size distribution in the Great Whin Sill also reveals an increase in the percentage of microphenocrysts towards the centre (e.g. Harrison, 1968). Strasser-King (1973) proposed that the magma was intruded as a crystal mush and that flow differentiation caused phenocrysts to accumulate in the centre of a sill where flow rates are highest. However, Thorpe and Macdonald (1985) suggested that differences in trace-element geochemistry between the chilled margin and interior of the sill imply multiple intrusions rather than flow differentiation. Where the sill thickness is about 50 m or more, a pegmatitic zone may be developed about one-third of the way down from the top. This can be observed in the thickest parts of the Great Whin Sill around the **Upper Teesdale** GCR site and is common in the generally thicker sills of the Midland Valley (e.g. see **South Queensferry to Hound Point** GCR site report). The pegmatitic patches and veins are characterized by clusters of long feathery augite crystals in an intergrowth of quartz and alkali feldspar. Ca-poor pyroxenes are absent from the pegmatitic areas and iron-titanium oxides are rare, but biotite and hornblende are important minor constituents. Patches and veins of pink aplitic fine-grained quartzofeldspathic material with almost square phenocrysts of sodic plagioclase are also common throughout both sill-complexes. Late-stage veins of fine-grained basalt, presumably from later pulses of magma, have been recorded in both sills and dykes.

Geochemical evidence of in-situ differentiation is most commonly observed in the Midland Valley Sill-complex, which reaches a thickness of *c.* 200 m, and in some of the thickest dykes in the Midland Valley which can be up to 50 m wide (Falconer, 1906; Tyrrell, 1909b; Flett in Peach *et al.*, 1910; Bailey in Clough *et al.*, 1911; Robertson and Haldane, 1937; Walker; 1952). A sill from the Bathgate area ranges from 48% SiO_2 in the chilled margin, to 56% SiO_2 in patches of pegmatitic quartzo-feldspathic rock and 71% SiO_2 in quartzo-feldspathic segregation veins (Falconer, 1906).

Like the alkaline basic intrusions of the Midland Valley (see 'Introduction' to Chapter 5), the tholeiitic intrusions of both the Midland Valley and northern England are commonly altered to a pale-cream or yellowish-brown rock, particularly close to contacts, fault planes or mineral veins (see Figure 5.8, Chapter 5). The original mineralogy has been changed to assemblages of quartz, illite, kaolinite, muscovite, rutile, anatase and carbonates by hydrothermal solutions believed to be of juvenile origin (Wager, 1929b; Day, 1930a; A.C. Dunham and Kaye, 1965; K.C. Dunham *et al.*, 1968; Ineson, 1968). In the Midland Valley this is termed 'white trap', whereas in northern England it is 'white whin' (see **Mollinsburn Cuttings** and **South Queensferry to Hound Point** GCR site reports).

In addition to the zones of 'white trap'/'white whin', the quartz-dolerites commonly exhibit a suite of late-stage hydrothermal minerals developed mainly in joints during the final stages of cooling. Quartz-calcite-chlorite veins are abundant locally in many of the dykes and sills of Scotland and northern England, and the Great Whin Sill is particularly noted for its late-stage zeolites (this mineralization is distinct from the epigenetic lead-zinc-fluorite-baryte mineralization of the northern Pennines which also affects the intrusions – see below). Perhaps the best-known and most spectacular examples are the widespread occurrence of pectolite on joint surfaces, common in the High Force area (see **Upper Teesdale** GCR site report) and along the Roman Wall (see **Steel Rigg to Sewingshields Crags** GCR site report). Other zeolite-type minerals found within the late-stage veins include analcime, apophyllite, chabazite and prehnite (Young *et al.*, 1991). Smaller amounts of chlorite, bowlingite, sericite, stevensite, albite, anatase and titanite occur as part of this phase of mineralization, commonly accompanied by abundant quartz and calcite. Mineralized amygdales are found locally in parts of Northumberland (see **Cullernose Point to Castle Point**, **Holy Island** and **Budle Point to Harkess Rocks** GCR site reports).

Midland Valley Sill-complex and dykes

The Midland Valley Sill-complex is exposed at numerous outcrops around the inner Firth of Forth (Figure 6.1). Its scarp features form many prominent landmarks, such as the **Lomond Hills** (see GCR site report) and Benarty Hill in Fife, and Cockleroy Hill and Carribber Hill in the Bathgate Hills. At Stirling, the vertical cooling columns form impressive natural defences on Castle Rock, and Abbey Craig forms a natural plinth for the Wallace Monument (Figure 6.4). Other well-known sill locations include North Queensferry (**North Queensferry Road Cuttings** GCR site), Hound Point (**South Queensferry to Hound Point** GCR site), Ratho, the Caldercruix-Shotts area and Kilsyth. Many of the associated dykes form distinct, often wooded, craggy ridges. The rock is still quarried extensively, mainly for aggregate, in the Ratho and Shotts areas, and smaller quarries are worked elsewhere from time to time. Several disused quarries have been landscaped for recreational

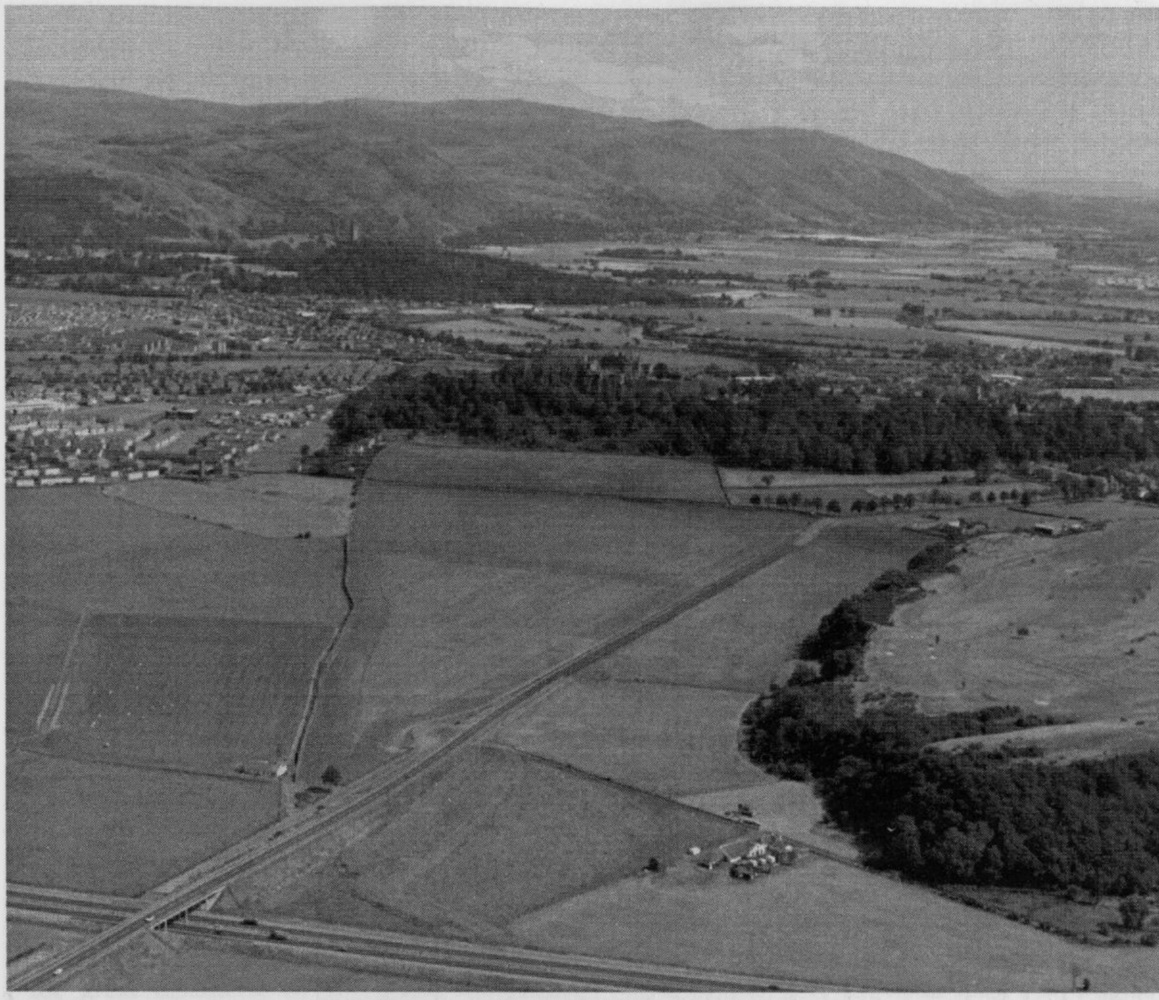

Figure 6.4 View from the air over Stirling. Outcrops of the SE-dipping Stirling Sill (Midland Valley Sill-complex) can be picked out by the tree-covered scarps that bound the golf course in the bottom right, Stirling Castle in the middle distance, and Abbey Craig (topped by the Wallace Monument) beyond. The Ochil Fault, which has fault-intrusions related to the sill-complex (e.g. the **Gloom Hill** GCR site) is responsible for the prominent south-facing scarp of the Ochil Hills in the distance. (Photo: British Geological Survey, No. D1940, reproduced with the permission of the Director, British Geological Survey, © NERC.)

use and many are, or have been, popular rock-climbing venues (e.g. Ratho, Ravelrig, Rosyth, Cambusbarron and Auchenstarry).

Dykes associated with the sill-complex cut rocks ranging from Archean to the Middle Coal Measures in age. The lowest stratigraphical horizon intruded by the sills is between the Knox Pulpit and Kinnesswood formations, at the Devonian–Carboniferous boundary, and the highest level is the Middle Coal Measures (Figure 6.5). Blocks of quartz-dolerite occur in sub-volcanic necks at Ardross and St Monance, which are considered to be late Stephanian in age (see Chapter 4), and plugs of olivine basalt and basanite may cut a quartz-dolerite sill in central Fife although this relationship cannot be proven (see **Lomond Hills** GCR site report). The tholeiitic magmatism in Scotland can therefore be constrained to have occurred between Duckmantian (Westphalian B) and late Stephanian times. K-Ar radiometric dates are within the range 305 ± 7 Ma to 280 ± 9 Ma (Fitch *et al.*, 1970; De Souza, 1974, recalculated by Wallis, 1989), broadly coeval with those obtained from the Whin Sill-complex.

The dyke-swarm associated with the Midland Valley Sill-complex is more extensive than that associated with the Whin Sill-complex and

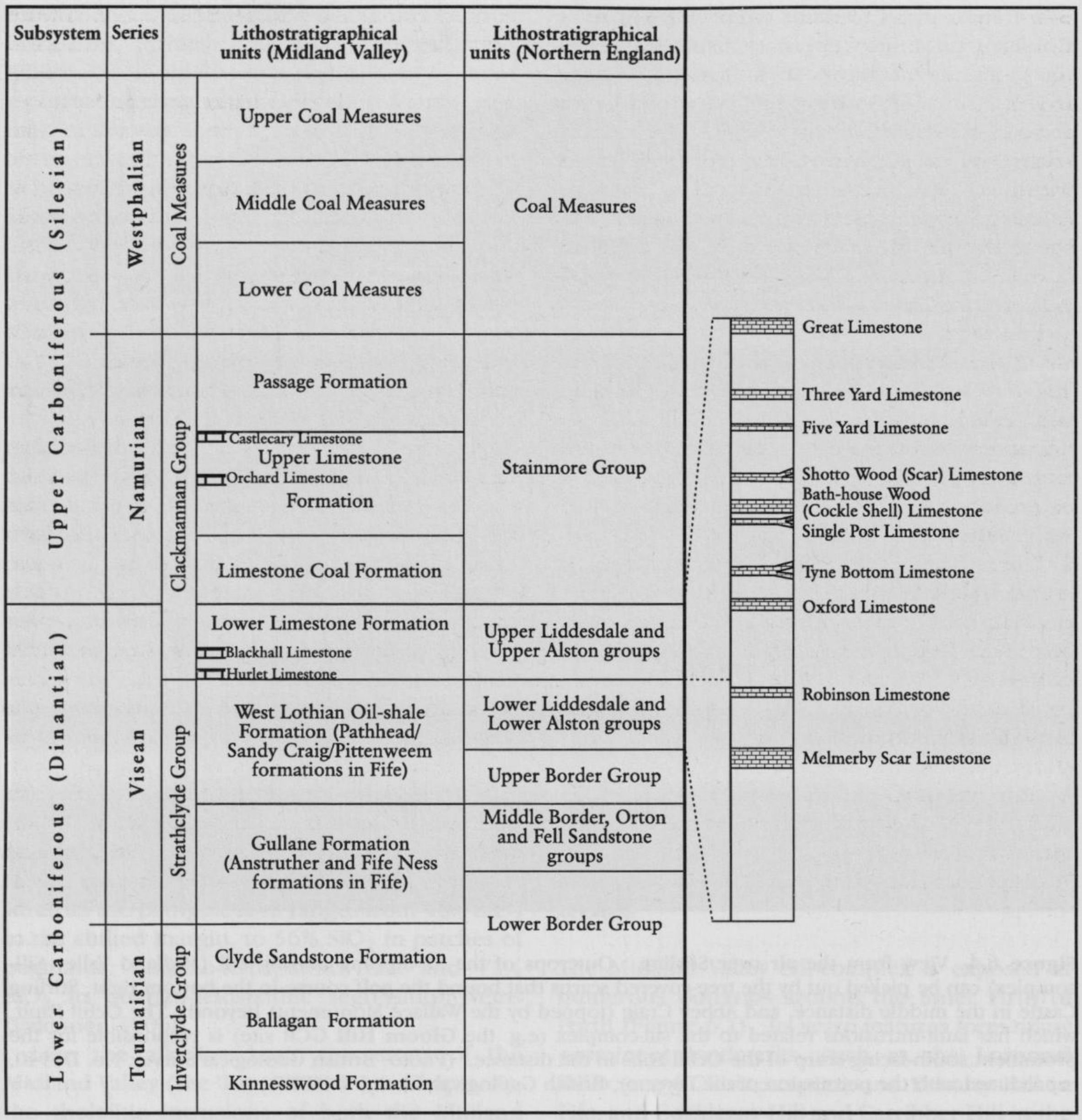

Figure 6.5 Simplified stratigraphical column showing the lithostratigraphy of Carboniferous rocks cut by the Stephanian tholeiitic sills and dykes of Scotland and northern England. In northern England, the Liddesdale Group is found in the Northumberland Basin whilst the Alston Group occurs on the Alston Block. The inset shows the position of major limestone bands that are transgressed by the Whin Sill-complex. After Browne *et al.* (1996); Chadwick *et al.* (1995); and Johnson (1997).

occurs across a 200 km-wide band stretching for over 300 km from the Outer Hebrides to the east coast of Scotland between Peterhead and Dunbar. The most comprehensive general review is that of Walker (1935), and details of individual dykes in some of the most dense parts of the swarm can be found in a preliminary paper (Walker, 1934) and in Geological Survey memoirs (Francis *et al.*, 1970; Armstrong *et al.*, 1985). Regionally the swarm is arcuate, trending 110° on the west coast, east–west in the central Midland Valley and 070° along the north-east coast. Locally some dykes are deflected to a north-east trend along the Highland Boundary Fault. In the Midland Valley, the dykes were emplaced partially along active or recently active

E–W-trending fault planes (see **Mollinsburn Cuttings** GCR site report, which describes a road cutting through the Lenzie–Torphichen Dyke). Individual dykes may be traced as *en échelon* offsets and for up to 130 km (e.g. from Loch Fyne to Tayside). They average 30 m in width but may reach up to 75 m onshore (Richey, 1939). Geophysical modelling has suggested that some dykes may reach widths of at least 1 km offshore (Smythe, 1994), though it is likely that these are composite bodies.

Quartz-dolerite also occurs as fault-intrusions along the significant E–W-trending Ochil Fault and may be observed at the **Gloom Hill** GCR site (Francis *et al.*, 1970). The age of these intrusions dates the latest movement on the fault during the Late Carboniferous north–south extension event at *c.* 303 Ma (Forster and Warrington, 1985).

The Midland Valley Sill-complex underlies an area of about 1920 km^2. In places the thickness is *c.* 200 m, much greater than the Whin Sill-complex, but the total volume is less, at *c.* 125 km^3 (Francis, 1982). The complex consists of several leaves, 25–100 m thick, which are linked by transgressive dyke-like intrusions along pre-existing fault planes ('fault risers'). A transgression can be seen clearly at the **Wallstale** GCR site where a vertical dyke-like intrusion links sills at two different structural levels. Other sills follow stratigraphical horizons for great distances, or are gently undulating forming long escarpments unaffected by faulting or sudden major transgressions (see **Lomond Hills** GCR site report).

There are a few sills that have been assigned tentatively to the tholeiitic sill-complex, but have atypical petrographical features. A sill of distinctive basalt at Binny Craig, West Lothian is mineralogically and geochemically similar to the quartz-dolerites, but is porphyritic, with small phenocrysts of plagioclase and augite (Lunn, 1928). Even more problematical is the Dalmahoy Sill, west of Edinburgh, which is olivine bearing but has many tholeiitic characteristics, including a glassy mesostasis extensively replaced by 'chlorophaeite'. A K-Ar date suggests a minimum age of 320 ± 7 Ma (*c.* 326 Ma with new constants) (De Souza, 1979), supporting an earlier Dinantian or Namurian age as was proposed by Campbell and Lunn (1925, 1927).

The sharp contacts of the sills with the host sedimentary rocks observed throughout the region provide evidence that the sediments were compacted and lithified prior to intrusion. Raymond and Murchison (1988) and Murchison and Raymond (1989) used borehole records to describe the thermal effects of sill emplacement on organic maturation in the Midland Valley. They found that thermal aureoles are extensive around the tholeiitic quartz-dolerite sills whereas there are limited thermal effects around earlier alkaline basic sills of similar thickness. The alkaline sills commonly show complicated relationships with the host sedimentary rocks indicating that these were unlithified on intrusion and still contained pore water (Walker and Francis, 1987).

Although the development of 'white trap' is widespread in both sills and dykes in the Midland Valley, mineralization is recorded from only a few tholeiitic dykes. The most instructive occurrences are in the Bathgate Hills, where boreholes have intersected several dykes, revealing an intimate relationship between faulting, multiphase dyke emplacement and mineralization (Stephenson, 1983). The dykes generally follow E–W-trending fault-lines, but they are also cut by sharply defined zones of fault-breccia implying both pre- and post-emplacement movement on the faults. Several dykes have broad zones of 'white trap', within which sticky black hydrocarbon occurs in calcite veins and as a coating to joints (Parnell, 1984). One dyke clearly shows at least two phases of intrusion, the earlier one being notably more affected by hydrothermal alteration and cut by calcite veins with baryte and traces of pyrite, chalcopyrite and fluorite; 'copper ore' is said to have been worked at one time from a baryte vein nearby. At Hilderston Mine a vein adjacent to a thin dyke contains two assemblages; Ni-Co-Ag-As adjacent to clastic sedimentary rocks, and Fe-Pb-Zn-S at a lower level adjacent to a limestone. Stephenson concluded that the dykes acted as both a heat source and a channel for the circulation of metalliferous brines that leached metals from the underlying oil-shale-bearing succession, local volcanic rocks and the intrusions themselves.

In the Renfrewshire Hills, near Lochwinnoch, copper was mined commercially in the mid-19th century from calcite-quartz-baryte veins on the margin of an E–W-trending quartz-dolerite dyke that cuts Dinantian lavas (Stephenson and Coats, 1983). In the Ochil Hills, lead- and silver-bearing veins seem to be closely associated with the Ochil Fault-intrusions (Francis *et al.*, 1970), particularly several of the veins in the Silver Glen, Alva, which occur on the margins of thin dykes parallel to the main intrusion (Hall *et al.*, 1982).

Whin Sill-complex and dykes

The quartz-dolerite of the Whin Sill-complex is generally tough and durable, weathering proud of the surrounding sedimentary rocks and forming spectacular crags and scarps that are a major feature of the scenery of north-east England (Warn, 1975). At the **Upper Teesdale** GCR site the Great Whin Sill forms the spectacular waterfalls on the River Tees at High Force and Cauldron Snout, both of which are major tourist attractions. In Northumberland, the Farne Islands, an important nature reserve, are outcrops of the Great Whin Sill, and both sills and dykes provide solid foundations for numerous castles, for example Dunstanburgh (**Cullernose Point to Castle Point** GCR site), Bamburgh (**Budle Point to Harkess Rocks** GCR site) and Holy Island (**Holy Island** GCR site). The Romans utilized the sill, building an important segment of Hadrian's Wall along an extensive scarp just north of the Tyne Valley (Figure 6.6; and Figure 6.25 – **Steel Rigg to Sewingshields Crags** GCR site). The durable rock has been extensively quarried for setts, railway ballast and roadstone, and quarrying continues to the present day, principally for roadstone and aggregate. Many of the most instructive exposures occur in quarries; the majority of these are long abandoned but several remain active, such as in the vicinity of Belford, north Northumberland, at Barrasford, Keepershield, Great Swinburne and Divethill in the North Tyne valley and near High Force in Upper Teesdale. Inevitably, commercial and conservationist interests in the rocks of the Whin Sill have clashed on occasions over threats to both geological and landscape features.

The youngest strata cut by the Whin Sill-complex or its associated dykes are Late Carboniferous, Duckmantian (Westphalian B) in age and pebbles of quartz-dolerite are known

Figure 6.6 Hadrian's Wall capping north-facing crags of the Great Whin Sill at Housesteads, Northumberland. (Photo: British Geological Survey, No. L1512, reproduced with the permission of the Director, British Geological Survey, © NERC.)

from breccias ('brockrams') in the Lower Permian (Saxonian) succession, near Appleby (Holmes and Harwood, 1928; K.C. Dunham, 1932). The intrusions were therefore probably emplaced during the time interval represented by the unconformity between the Upper Carboniferous (Westphalian) and Lower Permian rocks of the region (Randall, 1995b). This age of emplacement is re-inforced by K-Ar dating from a number of localities, suggesting a date of 301 ± 6 Ma (Fitch and Miller, 1967; recalculated with new constants), a U-Pb baddelyite date on the Great Whin Sill of 297.4 ± 0.4 Ma (M.A. Hamilton and D.G. Pearson, pers. comm., 2002), and an Ar-Ar plagioclase date of 294 ± 2 Ma on the Holy Island dyke-like intrusion (M. Timmerman, pers. comm., 2002). Two thin sheets of olivine-phyric dolerite that cut the Eycott Volcanic Group near Melmerby, west of the Pennines, have also been dated by K-Ar at 302 ± 8 Ma and have been interpreted as part of the Whin Sill-complex (Wadge *et al.*, 1972; recalculated with new constants). However, their petrography and geochemistry do not match the complex (Thorpe and Macdonald, 1985) and if the date is interpreted as only a minimum age, they could be related to the Cockermouth Lavas (see **Little Mell Fell Quarry** GCR site report).

The relationships of the Whin Sill-complex and dykes to structural events have been summarized by Jones *et al.* (1980), Turner *et al.* (1995) and Johnson and K.C. Dunham (2001), all of whom demonstrated that the intrusions post-date WSW–ENE compressional structures such as the Burtreeford Disturbance and the Holburn and Lemmington anticlines that mark the end of thermal subsidence in late Westphalian times. Johnson and K.C. Dunham (2001) also showed that they pre-date regional low open domes that drape the Weardale and Cheviot plutons and have been attributed to the stress relief and ensuing isostatic uplift that led to inversion of the Carboniferous basins and erosion in Stephanian time. However, there are conflicting views on the type of structural regime that permitted emplacement of the intrusions (Chadwick *et al.*, 1995). There is evidence of dykes having been intruded into strike-slip shear zones towards the end of the WSW–ENE compression (e.g. at Ratheugh Quarry near the **Longhoughton Quarry** GCR site). Or they may have been emplaced as a result of extension associated with the early stages of the uplift phase.

Dykes associated with the Whin Sill-complex are typically 3–10 m in width and follow north-east–south-west to ENE–WSW trends. Locally they form positive topographical features but many have now been quarried away and good quality natural exposures are rare. They occur in four widely separated subswarms, three of which could be regarded essentially as single discontinuous dykes with *en échelon* offsets (Figure 6.2). Some authors have actually used the term 'echelon' rather than 'subswarm'. The *en échelon* offsets have been attributed generally to the infilling of tensional fractures formed in response to regional compression, in a similar manner to small-scale tension gashes. However, geophysical investigations at the **Holy Island** GCR site have shown that some local offsets are caused by step-and-stair transgressions with short sill-like sectors. The most northerly subswarm, the Holy Island Subswarm, crops out to the north of the Great Whin Sill exposures and has *en échelon* offsets in a dextral sense (see **Holy Island** GCR site report). The High Green Subswarm extends for a distance of over 80 km south of the Cheviot Hills, converging slightly on the Holy Island Subswarm to cross the coastline at Boulmer. Its offsets are sinistral and some segments are *c.* 65 m in width. The St Oswald's Chapel Subswarm exhibits sinistral offsets on a broad scale and includes the Haltwhistle Dyke, well exposed at the **Wydon** GCR site where it forms a substantial feature on the banks of the River South Tyne. The Hett Subswarm includes several individual dykes to the south of Durham, near the southern limit of the Great Whin Sill exposures. A small group of dykes that cut the Berwickshire coast between Burnmouth and St Abb's have geochemical affinities with the Whin Sill-complex, rather than with the geographically closer Midland Valley dykes (Howard, 1999).

The Whin Sill-complex probably underlies at least 4000 km^2 of northern England (A.C. Dunham and Strasser-King, 1982), extending from the southernmost outcrops in Teesdale, west as far as the Pennine escarpment (most notably at High Cup Nick) and north to abundant exposures around Belford and the Farne Islands (Figure 6.2). There are also extensive exposures along the course of Hadrian's Wall and the Tyne Gap. Almost all of these natural exposures are of the Great Whin Sill, although this is known to split into several leaves in places. In Weardale, the Little Whin Sill is a distinctive separate intrusion represented by the **Greenfoot Quarry** GCR site. This slightly less fractionated sill, with olivine phenocrysts and slightly less SiO_2, is probably close in composition to the parental magma of the sill-complex and may have been intruded slightly earlier (A.C. Dunham and Kaye, 1965; Johnson and K.C. Dunham, 2001). A number of boreholes in the region have encountered the sills, for example at Crook (K.C. Dunham, 1948), Rookhope (K.C. Dunham *et al.*, 1965), Woodland (Harrison, 1968), Harton (Ridd *et al.*, 1970) and Throckley (A.C. Dunham *et al.*, 1972; Strasser-King, 1973; A.C. Dunham and Strasser-King, 1981). The thickest single leaf (73 m) crops out within the **Upper Teesdale** GCR site, but the Great Whin Sill is on average *c.* 30 m thick, with a tendency to thin towards its northern, western and southern margins (Francis, 1982). To the east, the sill splits into several leaves and occurs at three levels in the Harton borehole giving a total thickness of 90 m. The complete sill-complex has a volume of at least 215 km^3 and possibly much more, as it appears to thicken towards the east and may extend for some considerable distance under the North Sea (Francis, 1982).

The Great Whin Sill is considered to be saucer-shaped (Francis, 1982) and was intruded into a thick pile of Carboniferous strata ranging in age from Dinantian (e.g. Teesdale) to Westphalian (e.g. in the Midgeholme coalfield, north-east Cumbria). The intrusion changes stratigraphical level in a series of transgressive steps. This transgression of the sill may be observed clearly at the **Steel Rigg to Sewingshields Crags** GCR site together with evidence that transgression is commonly fault-controlled. The contacts of the sill are commonly reasonably sharp, implying that the host rocks were lithified prior to intrusion. In places in the Northumberland Basin, rafts of sedimentary rock detached from the host strata may be found within the body of the sill (e.g. at the **Cullernose Point to Castle Point** GCR site). At the **Budle Point to Harkess Rocks** GCR site the relationship between the sill and the sedimentary country rock is extraordinarily complex with numerous fragments and blocks of sandstone occurring within the sill. Here, the sedimentary rocks were probably disrupted prior to intrusion. Similar rafts of sedimentary rock can be observed at the **Longhoughton Quarry** GCR site and this site also provides evidence that the sill is unaffected by the major E–W-trending Longhoughton Fault. Elsewhere, such large inclusions are rare, although there is a notable example at Wynch Bridge in the **Upper Teesdale** GCR site.

The alteration of country rock, both above and below the Great Whin Sill, was recognized by Sedgwick (1827) as evidence of an intrusive origin and a very detailed study of local effects of the metamorphism was made by Hutchings (1895, 1898). More recent studies, again of restricted areas (Randall, 1959; Robinson, 1971), have been summarized by Robinson (1970), Randall (1995b) and K.C. Dunham (1990), but there have been no studies as yet of the metamorphic effects of the sill-complex across its entire outcrop. The maximum effect is observed where the sill is thickest and emplaced at the lowest stratigraphical level, in Upper Teesdale. Here limestones are recrystallized for over 30 m from the contact and mudstones are spotted for almost 40 m (e.g. in the Rookhope Borehole). Where the sill is thinner, as along the Pennine escarpment, only the beds very close to the contact are affected.

Relatively pure limestones, such as the Melmerby Scar Limestone in Upper Teesdale, exhibit extensive recrystallization to give a saccharoidal texture and readily disaggregate on weathering. This 'sugar limestone' gives rise to a distinctive suite of soils that supports the renowned alpine flora on Cronkley and Widdybank fells. Impure limestones are converted into calc-silicate rocks containing a wide variety of minerals including garnet, idocrase, wollastonite, diopside, feldspar, chlorite and epidote. The usually dark mudstones become light-coloured, hard porcellanous rocks ('whetstones') close to the contact, and farther away they develop spots, normally of chlorite, quartz and illite, but andalusite and cordierite have been recorded. In several places, layers of pyrite nodules within country rocks close to the margins of sills and dykes have been altered to pyrrhotite (e.g. at Wynch Bridge, **Upper Teesdale** GCR site). The presence of wollastonite and idocrase in particular indicate very high temperatures in the contact zone and in rafts of sedimentary rock within the sill. Robinson (1970) calculated a temperature of 720°C, well within the hornblende-hornfels or K-feldspar-cordierite-hornfels facies, grading outwards into the albite-epidote-hornfels facies. Both Hutchings and Robinson have also recorded petrographical and geochemical evidence for soda-metasomatism close to the contact in mudstones, which show a marked increase in Na_2O and the development of abundant albite. In places the adjacent dolerite has been converted to 'white whin' and Wager (1928, 1929b) suggested that at these localities the metasomatism of both dolerite and host rock was caused by late-magmatic hydrothermal fluids.

More distant effects of heat from both the sills and the associated dykes are seen in coal seams (Jones and Cooper, 1970); the metamorphic effect of three leaves of the Whin Sill-complex in the Harton Borehole can be detected at distances of 425 m above and 180 m below the sills (Figure 6.7). As with the various Midland Valley sills (see also Chapter 5), the rank of the coal is increased dramatically towards an intrusion, vitrinite reflectance increases, the texture changes and ultimately the coal becomes a natural coke (Jones and Creany, 1977; Creany, 1980). Around upper Weardale, vitrinite reflectance and textures suggest multiple episodes of metamorphism, and Johnson and K.C. Dunham (2001) have suggested that these may be due to injection of the Little Whin Sill and Great Whin Sill magmas at separate times.

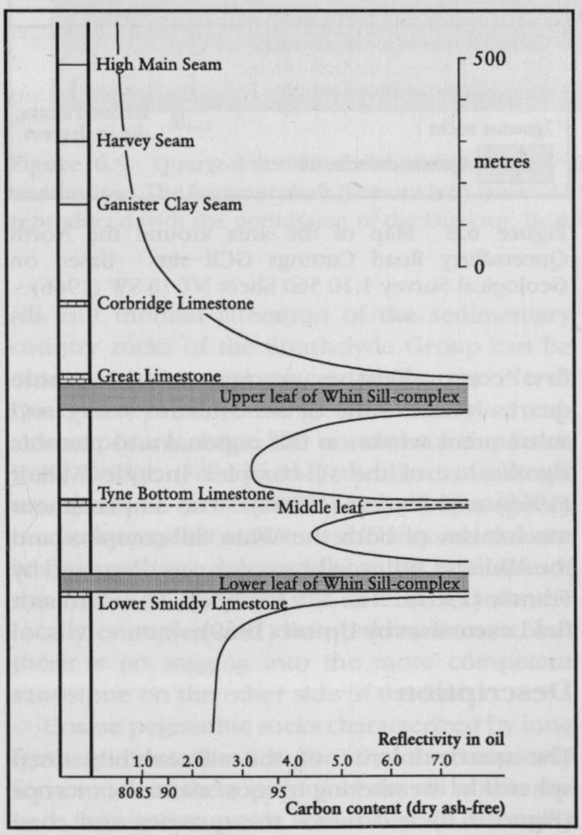

Figure 6.7 Variation in the rank of coals close to three leaves of the Whin Sill-complex in the Harton Borehole, Durham. After Jones and Cooper (1970).

In the Alston Block, the Whin sills and dykes are cut by mineral veins of the Northern Pennine Orefield (see **Upper Teesdale** GCR site report). The dolerite acts as a brittle wall-rock, like the limestones and the more massive sandstones, and hence is a favourable host for mineralization. In the Blackdene and Cambokeels mines of Weardale, the sill was a major host for fluorite ore-bodies, and at Settlingstones near Hexham, a wide vein of witherite was worked mainly in the Great Whin Sill and associated wall-rocks. At Closehouse Mine, a quartz-dolerite dyke within the Lunedale Fault that forms the southern boundary of the Alston Block, has been intensely mineralized. In this instance, earlier alteration to carbonate-rich 'white whin' has enabled subsequent extensive replacement by baryte to form an ore-body over 30 m wide in places (Hill and K.C. Dunham, 1968). K.C. Dunham (1990) has suggested that further good exploration targets exist where known veins may pass into dolerite wall-rock. The veins were deposited from hot aqueous solutions that appear to have come from depth and were channelled through the Weardale granitic pluton (K.C. Dunham *et al.*, 1965). The nature of these solutions has been the subject of great debate (Smith, 1995). Although there is some evidence from trace elements of a magmatic component (Ineson, 1969; Smith, 1974), most recent models invoke the deep circulation of connate brines or meteoric water that leached metals from various source rocks (K.C. Dunham, 1990). Evidence suggests that the primary mineralization occurred soon after the emplacement and cooling of the Whin Sill-complex (*c.* 284 Ma; K.C. Dunham *et al.*, 1968). For example, Young *et al.* (1985) have suggested that an unusual skarn assemblage containing magnetite, niccolite, galena and sphalerite, associated with the Teesdale Fault in Upper Teesdale, is evidence of mineralization during the final cooling of the sill, while metamorphism was still under-way. Hence it is possible that the deep magma chamber that supplied the sill-complex also provided the heat source to drive the convection system, even if it did not contribute directly to the mineralizing solutions. However, where mineral veins cut the sills and dykes, the dolerite has been altered to 'white whin' and it appears that metasomatism of the dolerite may have supplied Mg, Fe and Si to the circulating fluids (Wager, 1929b; A.C. Dunham and Kaye, 1965; Ineson, 1968; K.C. Dunham, 1990).

NORTH QUEENSFERRY (A90) ROAD CUTTINGS, FIFE (NT 126 807–NT 124 835)

S.C. Loughlin

Introduction

One of the most prominent and best-known features of the Carboniferous to Early Permian igneous activity in central Scotland is the Midland Valley Sill-complex. This quartz-dolerite sill-complex may be contemporaneous with the Whin Sill-complex of northern England and represents a brief period in Late Carboniferous times when magmas of tholeiitic affinity were generated (during much of Carboniferous and Permian times, transitional to alkaline volcanism predominated). The spectacular North Queensferry (A90) Road Cuttings GCR site comprises a 2.5 km-long road section along the A90 north of the Forth Road Bridge, together with several quarries to the east of the road (Figure 6.8). There are extensive fresh exposures of quartz-dolerite showing fine examples of chilled upper and lower margins, internal variations in rock-type and petrography, and late-stage segregation veins. No other site in the Midland Valley shows all these features of a quartz-dolerite sill in one continuous section.

The petrography of quartz-dolerite sills in the Edinburgh district has been described by numerous authors including Allport (1874), Geikie (1880), Teall (1888) and Falconer (1906). It was at North Queensferry that Allport described the presence of quartz in the dolerite, although he was of the opinion that it was a secondary mineral, and recognized pseudomorphs after olivine in the chilled margin. Peach *et al.* (1910) produced a thorough account of the petrography and field relationships of sills in the Edinburgh area in their Geological Survey memoir. This was a revision of the first edition (Howell and Geikie, 1861) that described the first published sheet of the Geological Survey of Scotland (Edinburgh, Sheet 32). Further geochemical study of the quartz-dolerites and segregation veins was carried out by Day (1928b). Walker (1935) provided the first comprehensive account of the whole quartz-dolerite suite of the Midland Valley, and subsequent works on the regional and tectonic significance of the sill-complex include Walker (1965) and Francis (1978a). The emplacement mechanism of both the Whin Sill-complex and the Midland Valley Sill-complex was discussed by Francis (1982). The site has been described as a field excursion by Upton (1969).

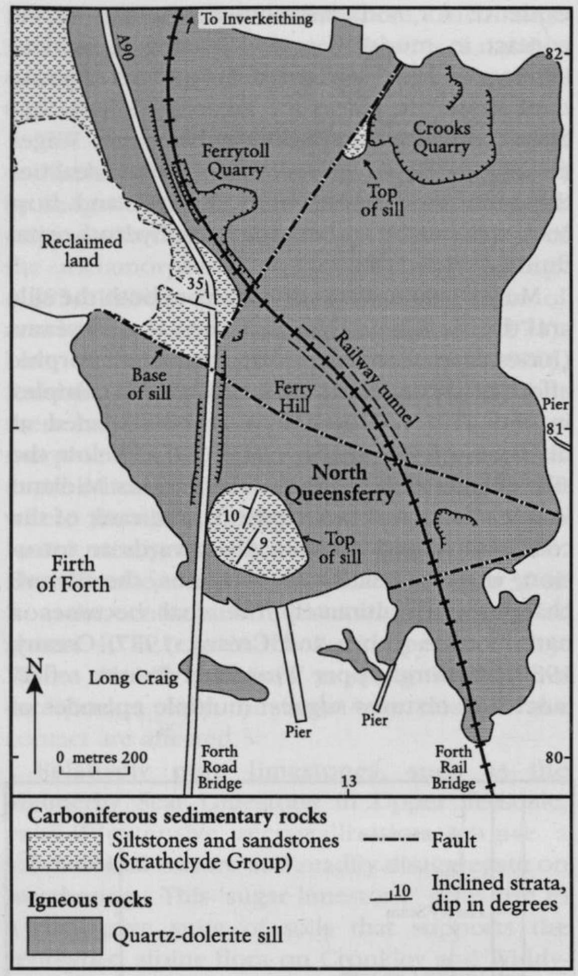

Figure 6.8 Map of the area around the North Queensferry Road Cuttings GCR site. Based on Geological Survey 1:10 560 Sheet NT 18 SW (1966).

Description

The quartz-dolerite of the sill exhibits deep spheroidal weathering in most natural outcrops (Figure 6.9) and hence the quarries and road cuttings provide far better illustrations of intrusive and petrographical features. The chilled upper and lower contacts of the quartz-dolerite

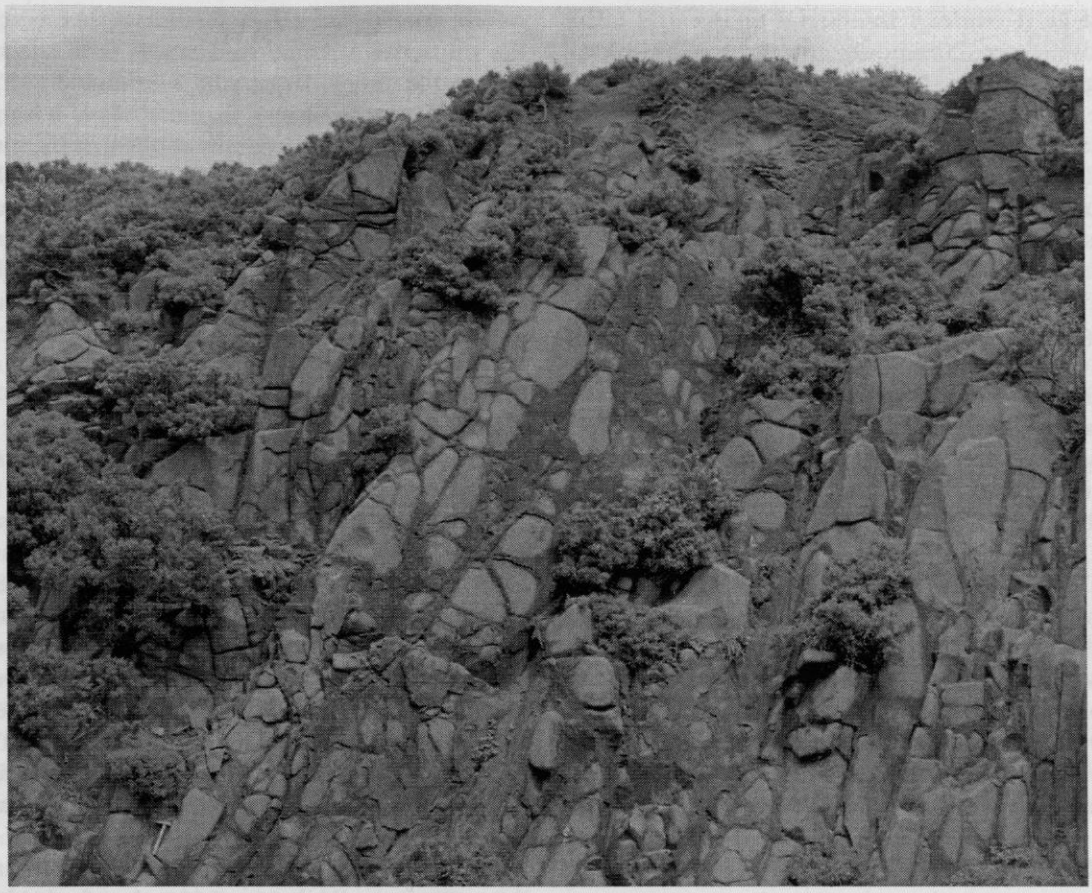

Figure 6.9 Quartz-dolerite of the Midland Valley Sill-complex at North Queensferry, showing spheroidal weathering. The hammer shaft (bottom left) is about 35 cm long. (Photo: British Geological Survey, No. D2580, reproduced with the permission of the Director, British Geological Survey, © NERC.)

sill and thermal alteration of the sedimentary country rocks of the Strathclyde Group can be observed at several places within the North Queensferry Road Cuttings GCR site. In a roadside exposure about 300 m north of the Forth Road Bridge (NT 126 811) the base of the sill cuts across an earlier normal fault that juxtaposes mudstones against sandstones. The quartz-dolerite has sagged into the mudstones on one side of the fault, and apophyses of dolerite intrude the locally crumpled and distorted mudstones, but there is no sagging into the more competent sandstone on the other side of the fault.

Coarse pegmatitic rocks characterized by long feathery clusters of augite crystals commonly form much of the top third of the sill at this site and segregation veins can be seen in many exposures. These segregations vary in grain size, texture, orientation and composition, but fine-grained to medium-grained quartzo-feldspathic types predominate. In the disused Ferrytoll Quarry (NT 127 816), by the railway line, there are some excellent examples. Here, the veins are pinkish-yellow and are very distinctive against the dark-blue-grey dolerite. One prominent vein is 12–20 cm wide and extends horizontally across a large part of the quarry walls before slanting upwards slightly. The vein divides at one point then rejoins, enclosing a lenticular mass of dolerite about 2 m long and 30 cm wide. There are also small discontinuous offshoots from the main vein. Other veins have different attitudes and some narrow veins are almost vertical. All veins are cut by the vertical cooling joints.

The petrography and geochemistry of the quartz-dolerite at this site is typical of the Midland Valley Sill-complex in general. It is medium grained to coarse grained and consists of mainly labradorite laths, sub-ophitic augite and Fe-Ti oxides. Intersertal quartz and alkali feldspar are commonly intergrown as micropegmatite. Pseudomorphs after olivine occur in the margins of the sill in the North Queensferry area (Allport, 1874).

The segregation veins typically comprise abundant small plagioclase laths, some orthoclase aligned parallel to the vein margins, and quartz; in addition they are commonly rich in micropegmatite. They contain fewer ferromagnesian minerals and Fe-Ti oxides than the dolerite, although primary biotite and hornblende are slightly more abundant. Some of the smaller veins have rather diffuse contacts, but larger veins typically have sharp margins although they are not chilled. The dolerite tends to be slightly finer grained near the margins of the segregation veins.

Day (1928b) analysed samples of quartz-dolerite from Prestonhill Quarry, Inverkeithing and Ferrytoll Quarry in this GCR site. Typical dolerites contain 47–49% SiO_2 whereas the most evolved segregation veins have values of 69–71% SiO_2. He also showed that the emplacement of the segregation veins did not affect the chemical composition of adjacent dolerite.

Interpretation

The intrusive nature of the Midland Valley Sill-complex was a subject of much debate and controversy during the 19th century (see 'Introduction' to this chapter) but the road cutting at this GCR site, which was unavailable to the early geologists, shows clearly that the sedimentary rocks overlying the quartz-dolerite are baked.

More recent investigations show that the Midland Valley Sill-complex is generally saucer-shaped with much of the intrusion following bedding planes down to the bottoms of basins where the intrusions are thickest (Francis, 1982). Francis proposed that sill emplacement was partly controlled by down-dip gravitational flow on gradients of up to 5°, from feeder dykes that extended to within 0.5 km and 1.0 km of the surface. Prior to this work, most authors (an exception being Robertson in Robertson and Haldane, 1937) had assumed that magma only flowed either upwards or laterally. Francis (1982) described the apophyses of dolerite extending from the sill down into the distorted shales at this GCR site and used this as an example of the downward (gravitational) component to magma movement.

The coarse-grained pegmatitic upper part of the sill that is seen so well at this GCR site is a feature of many large sills worldwide. This common profile shows that the sill is a single cooling unit that was totally molten at the time of emplacement (Francis, 1982). It is clear that the segregation veins, commonly with diffuse contacts, are related to the same parent magma as the dolerite and also that they were intruded while the sill was still cooling (features that were first recognized by Peach *et al.*, 1910).

Conclusions

The extensive A90 road cuttings at North Queensferry expose a typical representative of the Midland Valley Sill-complex. The GCR site is significant because of the abundance and easy accessibility of complex features that characterize large sills in general. Much early work on the Midland Valley Sill-complex was carried out in this district but this relatively recently exposed site is the only location where all the critical features may be observed. The upper and lower margins of the sill are chilled to a dark glassy rock and are clearly seen to bake the surrounding sedimentary rock. This is particularly significant at the upper contact as this unequivocally demonstrates that the body is an intrusion and not a lava. Irregular veins of quartz-dolerite can be seen penetrating the underlying sedimentary rocks. Within the sill, grain-size variations are clearly visible, from finer-grained margins to a medium-grained interior, with patches and veins of coarse-grained pegmatitic material in the upper third of the sill. Pale-coloured segregation veins are the most silicic part of the intrusion and form sheet-like bodies within the sill.

WALLSTALE, STIRLING (NS 763 900–NS 776 923)

S.C. Loughlin

Introduction

The Wallstale GCR site shows an exceptional example of the abrupt step-like transgression of the Midland Valley Sill-complex along a pre-existing fault-line. The transgressive nature of the sill-complex in relation to the Carboniferous strata it intrudes has long been recognized on the basis of borehole and mining data, but this important structural feature is rarely seen at outcrop. Three examples of such a structure are exposed in the Stirling area but this is the best exposed and the most representative. A fault plane containing a dyke-like body (a 'fault riser') links two quartz-dolerite sills that are at the same stratigraphical level but different structural levels. These field relationships prove that the magma was emplaced *after* movement on the fault but, despite the name 'riser', magma probably moved down the fault plane rather than up it.

The site is located about 4 km south-west of Stirling on a segment of the Midland Valley Sill-complex commonly known as the 'Stirling Sill' (Figure 6.1). The sill crops out along the western limb of the Clackmannan Syncline and forms a striking west-facing scarp extending south from Abbey Craig and Stirling Castle. As a result of transgression it is intruded at various stratigraphical levels within the Limestone Coal Formation.

The Stirling Sill is similar petrographically to other outcrops of the quartz-dolerite sill-complex except that it has pegmatitic patches a few centimetres wide, fringing quartzo-feldspathic veins in its lower part. Petrographical accounts include those by Goodchild (in Monckton, 1892), Monckton (1895) and Dinham (1927), and a detailed account of differentiation in the southern part of the sill was given by Walker (1952). General accounts, including the field relationships, were produced by Dinham and Haldane (1932), Robertson and Haldane (1937), Francis (1956), Read and Wilson (1959) and Francis *et al.* (1970). There are several aggregate quarries within the area of the site.

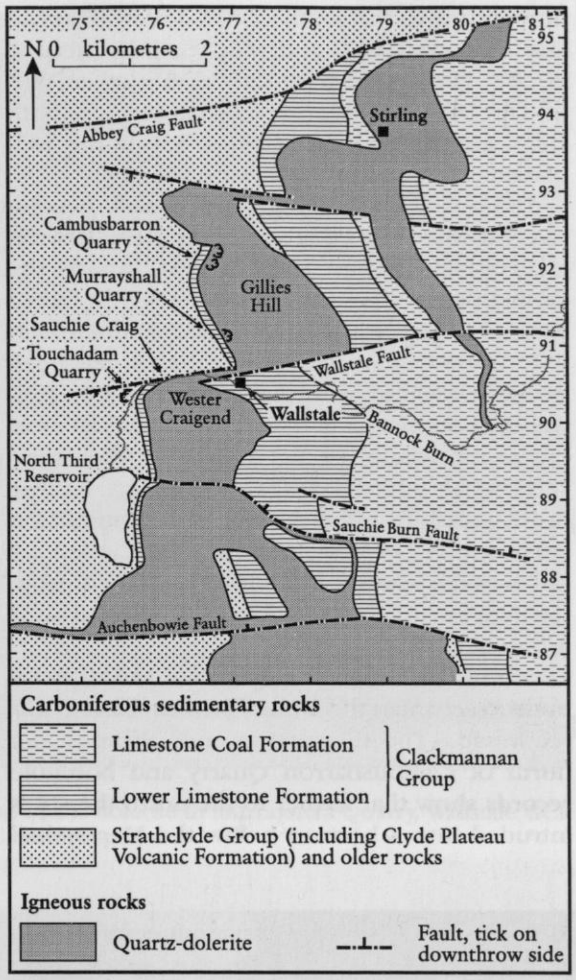

Figure 6.10 Map of the Midland Valley Sill-complex in the area around the Wallstale GCR site. After Read and Wilson (1959).

Description

The Stirling Sill is up to 100 m thick and dips at 5°–15° to the east. There are a number of significant E–W-trending faults in the area that pre-date the sill, one of which is known as the 'Wallstale Fault'. South of the Wallstale Fault the sill forms a continuous west-facing escarpment that runs from North Third Reservoir (NS 757 895) along the east banks of the Bannock Burn (Figure 6.10). In this area the sill is intruded near the base of the Lower Limestone Formation. The disused Touchadam limestone quarry lies at the foot of the escarpment just south of the Wallstale Fault. The dolerite escarpment swings abruptly to the east in the vicinity of the fault and forms an E–W-orientated line of crags (Sauchie Craig) that follow the southern banks of the Bannock Burn almost as far as Wester Craigend. Along the top of Sauchie Craig is a prominent ridge of quartz-dolerite that rises well above the upper surface of the sill. The sill dips down to the east beneath sedimentary rocks of the Lower Limestone Formation but the ridge continues beyond the eastern end of the crags (NS 769 906) as a dyke-like body 30–60 m wide. It extends for almost 400 m and then merges with the sill that forms Gillies Hill (NS 772 916) and the west-facing escarpment, north of the Wallstale Fault. The dyke-like ridge coincides almost exactly with the line of the Wallstale Fault. The fault has a downthrow to the south of 130–150 m (Dinham and Haldane, 1932) and yet the sill is intruded at the same stratigraphical level (lower part of the Lower Limestone Formation) on both sides, apparently linked by the dyke in the fault plane.

The quartz-dolerite has been quarried extensively to the north of the Wallstale Fault at the Murrayshall Quarry (NS 771 913), where the chilled base of the sill is in contact with baked coals, ironstones and mudstones. About 200 m ESE of the quarry, the base of the sill has been thrown down 13 m to the south by a late ESE-trending fault; this is one of the only places in the region where a quartz-dolerite sill is clearly seen to be affected by later faulting. Farther north, on the southern edge of Cambusbarron Quarry (NS 770 920) (Figure 6.11), there is a 4 m-thick sheet of dolerite separated from the base of the main sill by just over 1 m of indurated mudstone.

Below Cambusbarron Quarry is the site of a mine from which the Murrayshall Limestone was recovered. The sill outcrop ends abruptly just north of Cambusbarron Quarry and borehole records show that farther to the north the sill is intruded into a horizon below the Murrayshall Limestone. East of the GCR site, boreholes reveal that the sill divides into a number of distinct intrusive sheets; for example the Polmaise No. 5 shaft (NS 837 914) intersects at least three.

In general, the quartz-dolerite of the Stirling Sill is petrographically identical to that described elsewhere in the Midland Valley. Particularly good examples of hornblende and biotite, commonly mantling the augite and oxides, can be found in samples from Cambusbarron Quarry (Francis *et al.*, 1970). Samples showing skeletal patterns of iron oxide in the interstitial glass can also be found at this locality. As in many parts of the Midland Valley Sill-complex and the Whin Sill-complex, a pegmatitic zone occurs one-third of the way down from the top of the sill (Robertson and Haldane, 1937). However, an unusual feature of this sill is that there are additional quartzo-feldspathic veins in its lower part (Figure 6.12). These are fringed by a pegmatitic zone a few centimetres wide, comprising distinctive long feathery clusters of augite in a pink quartzo-feldspathic matrix (Walker, 1952; Francis *et al.*, 1970). The dolerite of the dyke-like 'riser' is a deeply weathered quartz-dolerite identical to that of the main sill.

Figure 6.11 Quartz-dolerite of the Midland Valley Sill-complex with strong vertical joints in Cambusbarron Quarry, Wallstale GCR site. The quarry face is 25–27 m high. (Photo: K.M. Goodenough.)

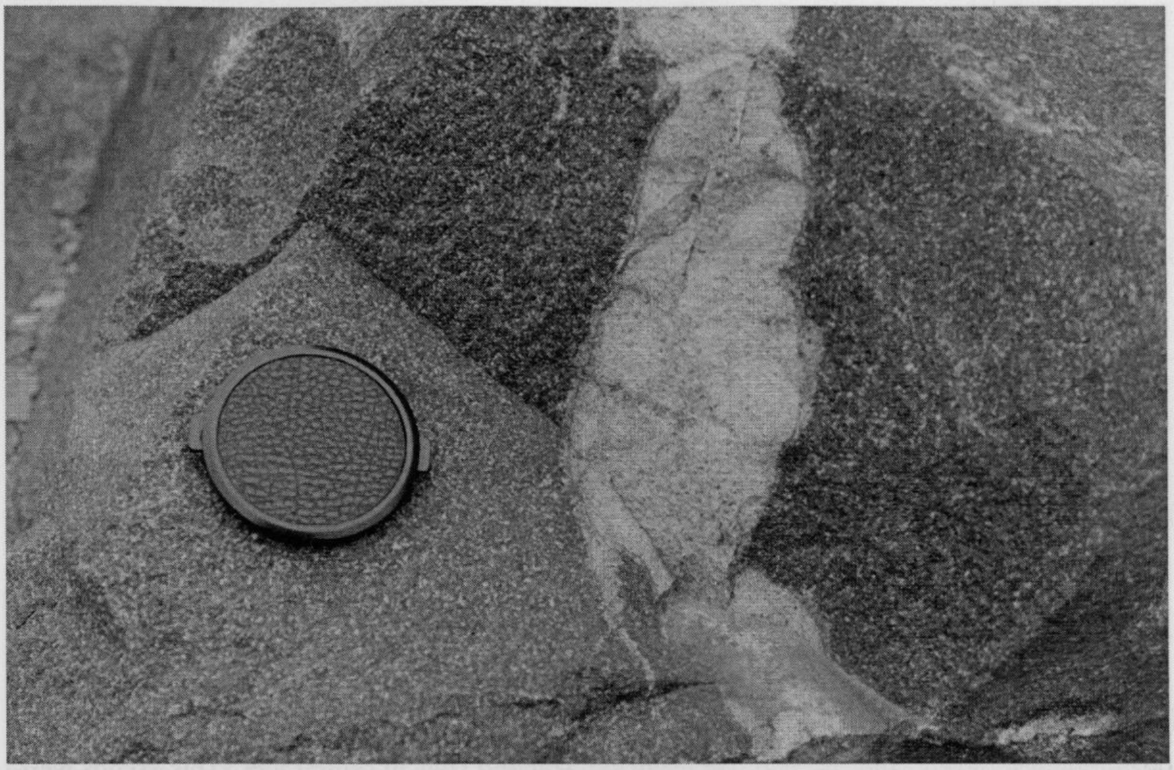

Figure 6.12 Pale-coloured felsic segregation vein cutting quartz-dolerite in Murrayshall Quarry, Wallstale GCR site. The lens cap is 50 mm in diameter. (Photo: K.M. Goodenough.)

Interpretation

The Midland Valley Sill-complex has been shown to be remarkably transgressive in relation to the sedimentary rocks into which it is intruded. Across the Midland Valley, sills are intruded into such widely differing stratigraphical levels that for many years the sill-complex was thought to represent numerous separate intrusions of different ages. In the coalfields adjacent to the Wallstale GCR site, borehole data and mine plans show that transgressions typically involve abrupt, step-like changes in horizon along dyke-like bodies known as 'risers'. Many of the risers exploit pre-existing fault planes but in some places the sill directly crosses a fault plane to a different stratigraphical level. Transgression is an important structural feature throughout the sill-complex but it is rarely seen at outcrop. The dyke-like body of quartz-dolerite at this site has been interpreted as a 'fault riser' and the site is unusual in that the transgressive dyke can clearly be seen to link the two sill outcrops. As a consequence of the transgression, the sills intrude the same stratigraphical horizon on both sides of the fault, despite a considerable offset on the fault prior to intrusion. The Wallstale Fault is one of three major E–W-trending faults in this area along which it is believed that transgressions have taken place, the others being the Auchenbowie and Abbey Craig faults. At the Abbey Craig Fault the sill does change stratigraphical horizon, but this was only confirmed by sub-surface evidence and hence Wallstale is certainly the clearest and most instructive example.

The quartz-dolerite sill is younger than most faulting in the Stirling area, the small fault near Murrayshall Quarry being the only proven example of a later fault. Immediately north of Cambusbarron Quarry, where the sill outcrop comes to an abrupt end, old mine plans show a small fault that was once considered to have thrown down the sill to the north. However, Dinham and Haldane (1932) and Read and Wilson (1959) considered it more likely that the abrupt drop of the base of the sill to the north is due to transgression of the dolerite into a lower level, possibly along an earlier fault. The dip-slope of the Stirling Sill in this area is dissected by many erosive channels, which appear to follow prominent joint planes. Read (1956) attributed this preferential erosion to hydrothermal alteration of the dolerite along the joints and was unable to detect any evidence of fault movement.

Francis (1982) showed that the shapes of the Midland Valley Sill-complex and the Whin Sill-complex approximate to a series of saucers, with the lowest, thickest parts coinciding with the centres of synsedimentary Carboniferous basins. The magma was probably introduced into the basins via marginal dykes and then flowed gravitationally from higher levels down bedding planes to the centre of the basins (Francis, 1982; see 'Introduction' to this chapter). The transgressive steps, such as the one observed at this site, are therefore believed to have occurred in a downward sense even though the old name 'risers' implies the opposite sense of movement. At Wallstale, the Midland Valley Sill-complex is at one of its lowest stratigraphical levels and is also very thick (explaining the fine development of in-situ differentiation features).

Conclusions

The Midland Valley Sill-complex has been shown to be remarkably transgressive, changing horizons within the Carboniferous succession both gradually and in a series of abrupt step-like jumps along fault planes. This behaviour, which results in complex surface and sub-surface relationships, is rarely observed at outcrop. At the Wallstale GCR site the relationships between the quartz-dolerite intrusion and a fault are clearly evident. The pre-existing E–W-trending fault let down the Carboniferous strata vertically by 130–150 m to the south. North of the fault, magma was intruded into the lower part of the Lower Limestone Formation and moved gravitationally down the gently inclined bedding of the strata towards the fault. It then flowed *down* the fault plane and intruded the same stratigraphical level on the south side of the fault.

The sill is relatively thick at this site and shows good examples of very coarse-grained pegmatitic dolerite and veins rich in pale quartzo-feldspathic minerals, both formed during the final stages of crystallization of the magma.

LOMOND HILLS, FIFE (NO 178 043–NO 248 068)

S.C. Loughlin

Introduction

The Midland Valley quartz-dolerite sill-complex is the most extensive and arguably the most important single intrusion in central Scotland. Detailed mapping and data from various mines in the adjacent coalfields have shown that it crops out around the margins of a large area (see 'Introduction' to this chapter, and Figure 6.1). It may remain at a constant level in the stratigraphical succession for long distances but it may also change horizon, often abruptly via fault-controlled dyke-like bodies or 'risers' (Dinham and Haldane, 1932) and often in a step-like manner (Knox, 1954; see **Wallstale** GCR site report). The somewhat undulatory nature of the sill in areas not generally affected by such structures is an important feature and is shown very clearly in the scarp face of the Lomond Hills in central Fife. This exends westward from East Lomond above the village of Falkland, towards West Lomond, then south via Bishop Hill to Kinneston Craigs above Scotlandwell (Figure 6.13). Throughout this outcrop the sill is intruded mainly into rocks of the Lower Limestone Formation of the (Upper Visean) Clackmannan Group. Small details of the contact phenomena associated with the sill are also of merit, providing evidence of partial melting of the intruded strata (Walker, 1958).

The site is also of considerable interest because it includes two sub-volcanic necks, with plugs of alkali dolerite and basanite, at the summits of East Lomond and West Lomond, and a basanite plug at the summit of Green Hill. Their respective age relations to the sill are of critical importance in any consideration of the evolution of igneous activity in the Midland Valley and consequently have been the subject of much debate (e.g. Irving, 1924; Walker and Irving, 1928; Macgregor and MacGregor, 1948; Francis, 1965; Browne and Woodhall, 2000).

The first published geological map of this area (Sheet 40) was released by the Geological Survey in 1867. The second edition of the map was published in 1898 and was

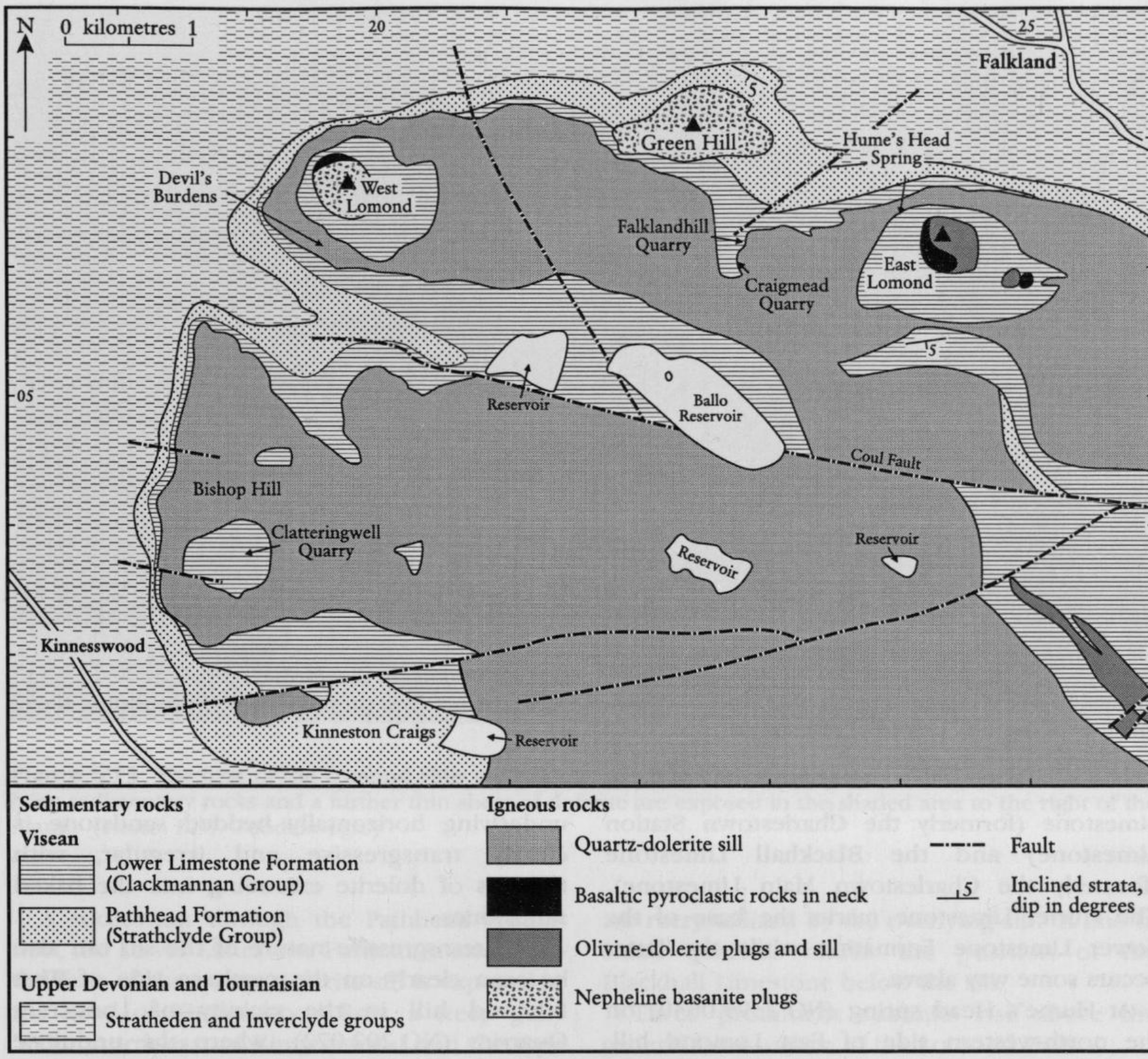

Figure 6.13 Map of the Midland Valley Sill-complex in the Lomond Hills. Based on Geological Survey 1:63 360 Sheet 40, Kinross (1971); and British Geological Survey 1:50 000 Sheet 40E, Kirkaldy (1999).

accompanied by two memoirs (Geikie, 1900, 1902). Since then the area has undergone a number of revisions and re-surveys and the latest edition was published in 1999 with accompanying sheet explanation and sheet description (Browne and Woodhall, 1999, 2000). Two field excursions, to the East Lomond and Bishop Hill areas of the site, have been described by MacGregor (1996).

The petrography and geochemistry of the quartz-dolerite at this GCR site is typical of the Midland Valley Sill-complex (Walker and Irving, 1928; see 'Introduction' to this chapter).

Description

The Midland Valley Sill-complex is here largely confined to the Lower Limestone Formation except at a few localities where it transgresses up as far as the Limestone Coal Formation or down into the Pathhead Formation (Strathclyde Group). Its total vertical range is in the order of 225 m and in thickness it varies from *c*. 50 m to *c*. 95 m. From East Lomond hill (NO 244 062) to Kinneston Craigs (NO 193 023), a distance of about 12 km, the sill forms a distinctive scarp (Figure 6.14) and is mostly intruded between two prominent limestones – the Hurlet

Figure 6.14 The escarpment formed by the Midland Valley Sill-complex on the north-west side of the Lomond Hills, with the basanitic plugs of West Lomond (nearest) and East Lomond (in the distance) protruding above the level of the sill. (Photo: P. Macdonald.)

Limestone (formerly the Charlestown Station Limestone) and the Blackhall Limestone (formerly the Charlestown Main Limestone). The Hurlet Limestone marks the base of the Lower Limestone Formation while the latter occurs some way above.

At Hume's Head spring (NO 2395 0630) on the north-western side of East Lomond hill, baked fossiliferous mudstones of the Lower Limestone Formation can be observed and, just a metre or so below, the top of the sill is also exposed. The position of the Blackhall Limestone is marked by a line of old workings which extend from just above the spring southwards to East Lomond Quarry. The limestone exposed in some of the workings is recrystallized but the top of the sill is not exposed in any. The rolling heather-covered slopes between East Lomond hill and West Lomond hill (NO 197 065) are composed of quartz-dolerite.

The lower part of the sill is clearly exposed at Craigmead Quarry (NO 228 061) (and also in Falklandhill Quarry (NO 228 062), but not as clearly), where it is spheroidally weathered, red-brown and columnar jointed (Figure 6.15). The base of the sill is chilled to a fine-grained, dense, black basaltic rock a few millimetres thick. The basal contact with underlying horizontally bedded sandstone is clearly transgressive and irregular, with tongues of dolerite extending into the baked sandstones.

The transgressive nature of the sill can also be seen clearly on the northern side of West Lomond hill in the vicinity of Longcraig Quarries (NO 202 072), where the undulose base cuts down through the sandstones and mudstones of the Lower Limestone Formation, through the Hurlet Limestone and into mudstones of the underlying Pathhead Formation. On the western slopes of West Lomond hill the sill rises back up through the sedimentary sequence to its original stratigraphical level just above the Hurlet Limestone in the Lower Limestone Formation. The quartz-dolerite in the area known as the 'Devil's Burdens' (NO 193 061) is deeply altered to a distinctive orange-brown coloured sandy gravel. The sill stays at this level along most of the western scarp of the Lomond Hills and the position of the underlying Hurlet limestone is marked by a line of small quarry workings. North of Bishop Hill (NO 1830 0440) a combination of columnar jointing and weathering of the sill has formed an impressive needle of rock which is popular with climbers.

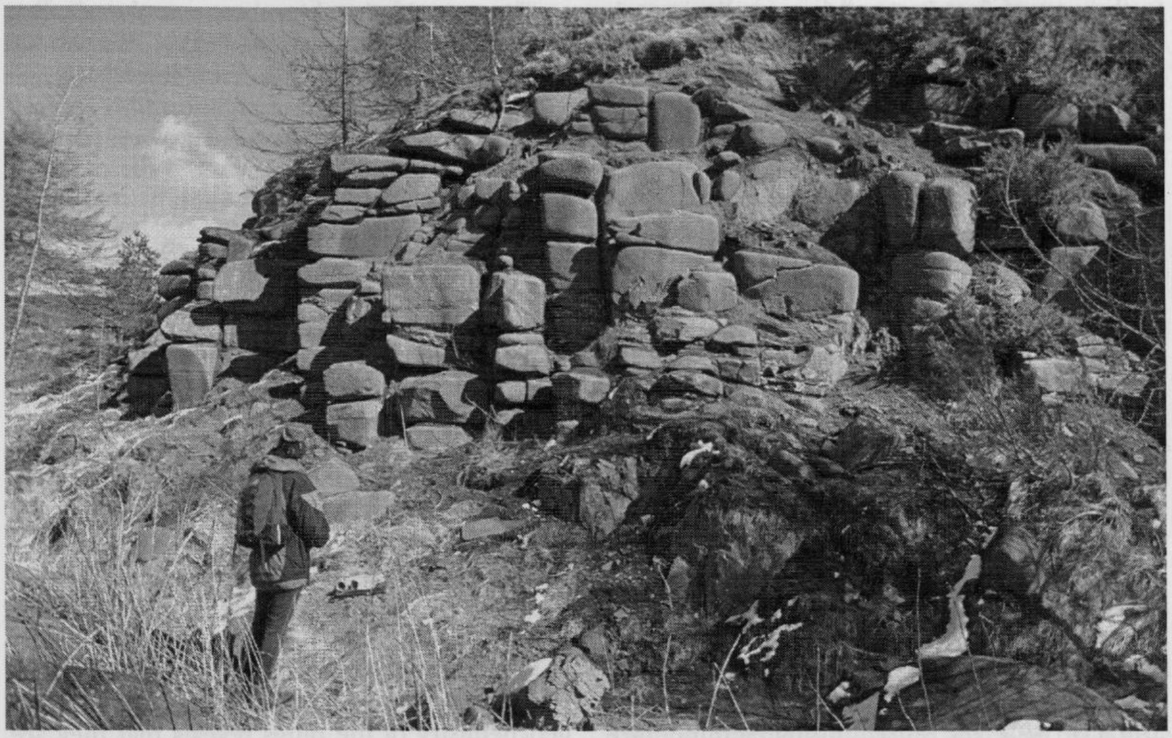

Figure 6.15 The base of the Lomond Hills quartz-dolerite sill in Craigmead Quarry. The contact, the underlying sedimentary rocks and a further thin sheet of dolerite are exposed in the shaded area to the right of the figure. (Photo: K.M. Goodenough.)

A succession through the Pathhead Formation, the Lower Limestone Formation and up to the base of the quartz-dolerite sill is exposed at the head of Kinnesswood Row, a steep gully 500 m north-east of Kinnesswood and the type locality for the Kinnesswood Formation. The top metre or so of sandstone has been recrystallized by the sill, and the highest mudstone bed is bleached and hardened. The basal margin of the sill is chilled, and above, the characteristic crude columnar joints and spheroidal weathering of the sill can be observed.

Around the summit of Bishop Hill, the Blackhall Limestone above the sill has been quarried extensively; in this area it is relatively thick due to microbial bioherm build-ups. The limestone is typically bedded and very rich in crinoids; in addition, two distinct reef mounds can be identified at Clatteringwell Quarry (NO 1875 0375). Just south of White Craigs, above Kinnesswood village (NO 184 032), the sill changes horizon abruptly to a level above the Blackhall Limestone so that on the southern side of Bishop Hill, several metres of fossiliferous sandstones and mudstones above the limestone are recrystallized by the overlying sill. A line of small quarries marks the position of the Blackhall Limestone below the sill.

Three prominent summits rise above the general land surface of the Lomond Hills.

East Lomond (442 m) is a steep-sided, rounded hill with a distinct 'shoulder' on its western side. It stands above the scarp formed by the sill just south of Falkland. The gentle lower slopes of the hill are underlain by the Lower Limestone Formation, which directly overlies the sill. The summit of the hill is composed of a dark-green to black analcime-bearing olivine-dolerite. In hand specimen olivine phenocrysts are conspicuous and alter to a reddish colour on weathered surfaces. Crude joints radiate outwards from the centre of this intrusive body suggesting that it is probably a plug (Irving, 1924). Vesicles with an infilling of green serpentine occur widely but the rock generally has a 'fresh' appearance in contrast to the deeply weathered quartz-dolerite sill. The shoulder of the hill is composed of a friable pale-olive-green volcaniclastic breccia containing angular fragments of altered basaltic rock. Just to the east of East Lomond is a smaller, poorly exposed outcrop of olivine-dolerite, also with a basaltic breccia at its eastern margin. The olivine-dolerite of the main plug comprises mainly large olivine phenocrysts, laths of labradorite and intersertal (rather than ophitic) mauve-pink titaniferous augite. Accessory minerals include titaniferous magnetite, apatite and analcime with some devitrified glass.

West Lomond (522 m) is a cone-shaped hill also standing above the scarp of the sill. The hill is composed of nepheline basanite with a thin sliver of breccia on its northern margin, and is interpreted as a sub-volcanic neck and plug. The lower slopes are composed of sedimentary rocks of the Lower Limestone Formation which overlie the sill. Two smaller plugs occur just east of West Lomond (Browne and Woodhall, 2000).

Between East and West Lomond is the rounded summit of Green Hill (305 m), which lies below the scarp of the sill. It is composed of black, fine-grained nepheline basanite, slightly finer grained than that of West Lomond. The contacts with the surrounding sedimentary rocks are not exposed but it is assumed to be a plug (M.A.E. Browne, pers. comm., 2000).

Interpretation

Geikie (1900) recognized the intrusive nature of the Midland Valley Sill-complex and described the transgressive contacts and chilled margins in this area. He cited the undulose nature of the sill in the Lomond Hills as a particularly good example of transgression. The recrystallized limestones and baked mudstones above the sill at East Lomond provide clear evidence of the intrusive nature, and the sharp contacts with host sedimentary rocks observed throughout the GCR site indicate that the sediments were compacted and lithified prior to intrusion.

Walker (1958) investigated the contact between the sill and the sandstones and mudstones of the Lower Limestone Formation at East Lomond and found petrographical evidence for remobilization of the sedimentary host rocks. He observed a zone of alkali-feldspar-rich material, 1–3 mm thick, along the contacts; in places, thin veins of this material actually cut through the adjacent sedimentary layers but they do not cut the sill. The source of this remobilized material was thought to be the thin mudstone laminae intercalated with the sandstones.

The age relationships between the alkaline basic plugs and the tholeiitic sill at this site are equivocal, but historically they were regarded as fundamental to determining the overall sequence of Carboniferous–Permian igneous events. Geikie (1900) interpreted the outcrops that form the summits of East and West Lomond as erosional outliers of sills intruded above the main sill. However, Irving (1924) and Walker and Irving (1928) concluded that they are irregular plugs marking the sites of Late Carboniferous necks that penetrated the sill, and this interpretation was re-asserted by Macgregor and MacGregor (1948). Francis (1965), whilst accepting the interpretation of plugs, pointed out that there is no satisfactory field evidence for their age relationship with the sill. No contacts are exposed, no xenoliths of quartz-dolerite have been found in the plugs or associated breccias and, in addition, the East Lomond olivine-dolerite is petrographically similar to olivine-dolerite sills demonstrably older than the Midland Valley Sill-complex. The petrography and geochemistry of the plugs reveals that they are related to a separate period of alkaline volcanism, but this could be either before or after emplacement of the tholeiitic sill-complex. There is no doubt that olivine-dolerite sills, plugs and contemporaneous volcanic rocks were emplaced throughout Fife during a period of multiphase alkali magmatism throughout mid- to late Carboniferous and Early Permian times (see 'Introduction' to Chapter 4; and 'Introduction' to Chapter 5). The more highly silica-undersaturated alkaline basic rocks, such as nepheline basanites, are generally assigned to the later phases of igneous activity in the Midland Valley, but Browne and Woodhall (2000) consider that the alkaline basic plugs in the Lomond Hills area were intruded during late Visean or Namurian times, when the sediments were still unlithified and contained pore water. The volcaniclastic breccias exposed at East Lomond and West Lomond are therefore assumed to be the products of explosive volcanism, which occurred as a result of magma–water interaction.

Conclusions

The Lomond Hills GCR site is representative of the Midland Valley Sill-complex, a geological feature that has a profound effect on the topography of eastern central Scotland. At this site the quartz-dolerite sill and underlying sedimentary rocks form a steep escarpment that extends for a total distance of about 12 km. The margins of the sill are gently undulating and in several places the basal contact can be seen to transgress through several levels of the underlying strata. There is also evidence that the thermal effects of sill emplacement have partly melted the sedimentary rocks immediately adjacent to the sill. Baking and recrystallization of sedimentary rocks above the quartz-dolerite provides evidence that it is an intrusive sill and not an extrusive lava. Sub-volcanic necks with plugs of alkaline basic rock occur above the escarpment and provide evidence of explosive volcanic activity in the region. The composition of the plugs suggests that this volcanism was unrelated to the sill, but the exposed field evidence cannot resolve whether it was earlier or later. The age relationships at this site were once regarded as crucial to determining the sequence of igneous events in the Midland Valley and consequently have been the subject of much debate.

GLOOM HILL, DOLLAR, CLACKMANNAN (NS 964 990)

S.C. Loughlin

Introduction

The geological relationships exposed in the quarry, on the southern margin of Gloom Hill, 0.5 km north of Dollar, are of considerable importance in understanding the relationships between magmatism and tectonism in the Midland Valley during Late Carboniferous to Early Permian times. The Ochil Fault, one of the most important faults in the Midland Valley, is exposed in the quarry along with a quartz-dolerite intrusion that was emplaced along the fault plane. Geochemical evidence (e.g. Macdonald *et al*., 1981) suggests that this intrusion, and others intruded into the fault zone nearby, are associated with the Midland Valley Sill-complex.

The E–W-trending Ochil Fault is a long-lived structure that is responsible for the impressive escarpment of the Ochil Hills, east of Stirling (Figure 6.4). The tectonic significance of the fault was known long ago and the impressive vertical displacement (up to 4 km) was also recognized (e.g. Geikie, 1900). Nevertheless the tectonic evolution of the region and the subsurface structure of the fault have proved to be intriguing problems up to the present day (e.g. Haldane, 1927; Francis *et al*., 1970; Gibbs, 1987; Coward and Gibbs, 1988; Rippon *et al*., 1996). To the north of the fault the Ochil Hills are composed of late Silurian to Early Devonian lavas and volcaniclastic rocks. These are juxtaposed against Westphalian Coal Measures that form the low-lying undulating topography to the south. Although the fault may have been initiated in Early Devonian times, the main movement is believed to have occurred in Late Carboniferous times during a period of north–south extension that was accompanied by intrusion of quartz-dolerite magma along the fault plane (Rippon *et al*., 1996). Dating of the fault-intrusions at *c*. 303 Ma therefore provides an age for this phase of extension (Forster and Warrington, 1985).

Five quartz-dolerite intrusions occur along the main part of the Ochil Fault near Dollar (termed the West Ochil Fault by Rippon *et al*., 1996) and these are exposed in the burns running down the southern scarp of the Ochil Hills (Figure 6.16). The Gloom Hill GCR site reveals part of the largest intrusive body, which is over 3 km long and up to 300 m wide. Two other quartz-dolerite intrusions occur in the Arndean Fault which branches south-eastwards off the Ochil Fault to the east of Dollar and probably takes up a large part of the throw.

The area around the Ochil Fault has experienced recent seismic activity and this has been described by a number of authors (e.g. Davison, 1924; McQuillan in Francis *et al*., 1970).

Description

The quartz-dolerite intrusion in the quarry at Gloom Hill is at least 40 m wide and the northern margin is chilled against scoriaceous, vesicular, purple- and green-tinged andesitic lavas and volcaniclastic rocks of the Ochil Volcanic Formation (Haldane, 1927; Francis *et al*., 1970). This northern contact of the intrusion hades at 63° to the south (Figure 6.17). The southern contact is not visible but a southerly hade of 72° is revealed at the southern margin of a quartz-dolerite intrusion at Castle Craig Quarry, Tillicoultry, 4 km to the west, where the exposed chilled contact lies against deformed Westphalian strata (Haldane, 1927). There, the contact is undulose and shows how intrusion of the dolerite has distorted the fault plane (Francis *et al*., 1970).

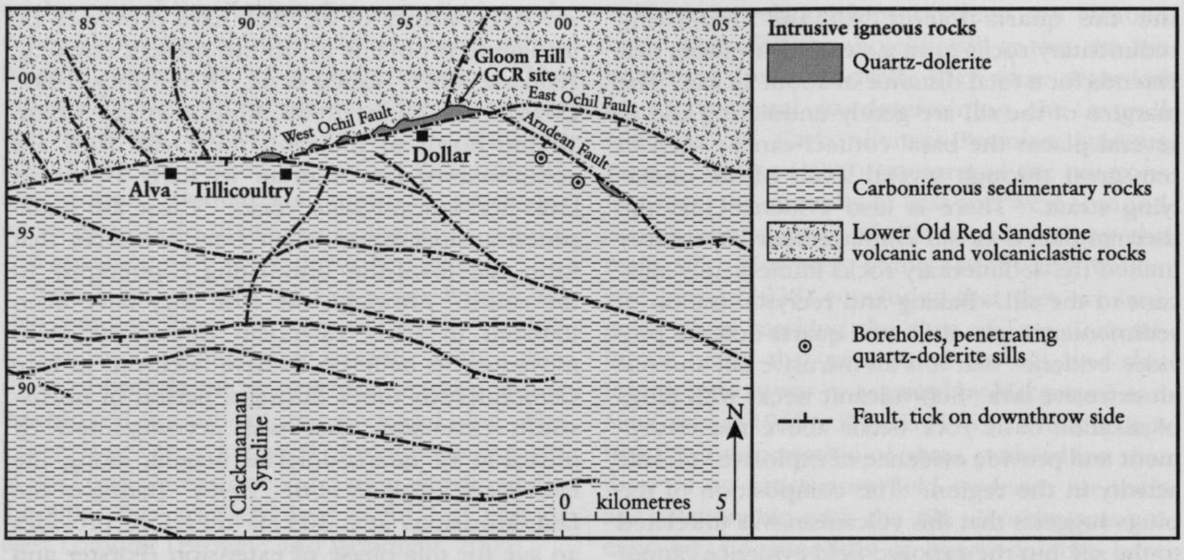

Figure 6.16 Map of the area around the Gloom Hill GCR site. After Rippon *et al.* (1996).

The quartz-dolerite in the quarry at Gloom Hill is of very similar composition and petrography to those of the Midland Valley Sill-complex, with abundant quartz and micropegmatite (Francis *et al.*, 1970; Macdonald *et al.*, 1981). The grain size clearly increases inwards from the northern margin towards the central part of the intrusion but overall it is finer grained than the usual sub-ophitic variety of the sill-complex. Some leucocratic segregation veins up to 2 cm thick can be seen on the quarry face but they are not a conspicuous feature.

Figure 6.17 View towards the east of the exposures of the Ochil Fault-intrusion in the quarry at Gloom Hill, with Siluro–Devonian lavas on the left, quartz-dolerite of the fault-intrusion on the right, and the contact parallel to the quarry face. (Photo: I.T. Williamson.)

Interpretation

The Ochil Fault plane is seen to be inclined to the south in three separate outcrops, including the quarry at Gloom Hill. However, early seismic evidence, based partly on the location of earthquake epicentres, suggested that the hade is to the north and the fault was therefore interpreted as a reverse fault by Davison (1924). Haldane (1927) discussed the contradictory seismic and geological evidence and suggested a number of solutions: (a) that that the seismic effects may have been caused by simultaneous movements along a series of NNW-trending faults on the north side of the Ochil Fault; (b) that they were caused by movement on a small subsidiary fault; or (c) that the hade of the fault is only to the south near the surface and is to the north at depth. MacQuillen (in Francis *et al.*, 1970) re-emphasized the strong seismic evidence for a northerly hade and proposed that the southerly dip of the fault exhibited at the surface is not a feature in the deeper part of the fracture zone (Haldane's option (c)). Since then, a number of contrasting tectonic models have been proposed. For example, Gibbs (1987) developed a complex tectonic model for the Kincardine Basin and suggested that the Ochil Fault is a reverse fault, dipping to the north, whereas Dentith (1988) proposed that the fault dips steeply to the south. The matter is clearly unresolved, though more recent seismic reflection studies reveal a southerly dipping fault plane to at least a depth of 2.5 km (Rippon *et al.*, 1996).

Estimates of the maximum total displacement on the West Ochil Fault are of the order of 4 km (Geikie, 1900; Francis *et al.*, 1970; Rippon *et al.*, 1996). The fault probably originated in Devonian time, prior to deposition of the Upper Red Sandstone, and acted as a control on subsidence and deposition throughout the Carboniferous Period. However, the main movement on the fault must have been late or post Westphalian in age, since Westphalian strata are juxtaposed against Lower Devonian volcanic rocks. The contact relationships exposed at Gloom Hill and Castle Craig Quarry indicate that the intrusive magma exploited the pre-existing fault plane as suggested by Haldane (1927), but Rippon *et al.* (1996) suggested that the presence of magma could also have facilitated later movement on the West Ochil and Arndean faults.

The quartz-dolerite intrusion at Gloom Hill, its margins and an aplitic vein were analysed by Macdonald *et al.* (1981), who confirmed that they are part of the large tholeiitic suite of sills and dykes emplaced during Late Carboniferous times in the Midland Valley of Scotland. Francis (1982) suggested that the Ochil Fault-intrusions may be feeders to the Midland Valley Sill-complex. However, the Ochil Fault only hosts intrusions in its central part and hence does not appear to be the location of a major feeder dyke system. On a more local scale, boreholes have revealed the presence of quartz-dolerite sills at about the level of the Castlecary Limestone (at the top of the Upper Limestone Formation) close to the Arndean Fault on the southern (downthrown) side (Rippon *et al.*, 1996). It seems quite likely that these may be linked to the Ochil Fault-intrusions.

Westphalian coals at Dollar show enhanced ranking which has been interpreted as a localized thermal effect of the Ochil Fault-intrusions (Rippon *et al.*, 1996) and the intrusions have a radiometric age of 303 ± 5 Ma (Forster and Warrington, 1985). It is therefore assumed that emplacement of the quartz-dolerite intrusions throughout the Midland Valley was in response to a brief but important phase of north–south extension in latest Carboniferous times (Rippon *et al.*, 1996).

Conclusions

At the Gloom Hill GCR site the Ochil Fault plane is clearly exposed and is intruded by a 40 m-wide quartz-dolerite body associated with the Midland Valley Sill-complex. The E–W-trending Ochil Fault played a critical role in the tectonic evolution of the Midland Valley in Late Carboniferous and Early Permian times and has had a major effect on the topography of the district. The fault is steeply inclined to the south at present surface levels, but studies of local minor earthquakes suggest that this may not be the case at depth. The maximum vertical displacement of 4 km juxtaposes Siluro–Devonian volcanic rocks against Westphalian coal measures, so the main movement on the fault probably occurred in Late Carboniferous times. At least some of this movement may have been contemporaneous with the intrusion of magma along the fault plane, which may have eased movement along the fault. A radiometric age of *c.* 303 Ma for this fault-intrusion is therefore believed to date the latest extensional movement on the Ochil Fault that coincided with a brief period of regional north–south extension.

MOLLINSBURN CUTTINGS (A80), NORTH LANARKSHIRE (NS 716 718)

S.C. Loughlin

Introduction

The E–W-trending dyke-swarm associated with the Midland Valley Sill-complex contains tholeiitic basalt and quartz-dolerite dykes between 3 m and 75 m wide, discontinuous outcrops of which may be traced for up to 300 km. The Mollinsburn Cuttings GCR site on the A80 Glasgow to Stirling road reveals an excellent section through the Lenzie–Torphichen Dyke, a typical quartz-dolerite dyke that can be traced for over 40 km. It forms a conspicuous feature along much of its length and partially coincides with pre-existing E–W-trending faults.

The first Geological Survey map of this area (Sheet 31, Airdrie) was published in 1875. It was re-surveyed and re-published in 1924 and again in 1992 as Sheet 31W, the latter with an accompanying memoir (Forsyth *et al.*, 1996). Based on the field relationships exposed at this site and nearby, early workers suggested that the dykes of the E–W-trending swarm acted as feeders for the Midland Valley Sill-complex (Tyrrell, 1909b; Clough *et al.*, 1925). More recently, geochemical studies have confirmed that the dykes and sills are comagmatic (Macdonald *et al.*, 1981; Howard, 1999), and their emplacement mechanism has been discussed in great detail by Francis (1982). The Lenzie–Torphichen Dyke is one of a few in the Midland Valley that can be demonstrated to have acted as a 'fault riser', facilitating the transgression of sills between different stratigraphical levels (see also **Wallstale** GCR site report).

Description

The Lenzie–Torphichen Dyke, which is exposed intermittently from north of Bishopbriggs (NS 573 714) in the west to Cairnpapple Hill (NS 990 720) in the east, has an overall length of over 40 km and an average breadth of 40 m. The dyke is resistant to weathering in comparison to the host sedimentary rocks and therefore forms a distinctive topographical feature that is seen particularly well over a distance of 5 km, between Millersneuk, Lenzie (NS 665 718) and Mollinsburn (NS 720 717).

At Mollinsburn there are two parallel branches of the dyke that cut the Upper Limestone Formation (Figure 6.18). The northern branch is seen in road cuttings and as a gorse-covered ridge, Mollin Craig, to the west of the road, where horizontal columnar joints perpendicular to the dyke margins are conspicuous (Figure 6.19). The central part of the dyke is medium grained, becoming finer grained towards the chilled margins which are commonly glassy. In common with other quartz-dolerites of the Midland Valley Sill-complex and dykes, the central part contains feldspar laths (bytownite or labradorite mantled by oligoclase), ophitic to sub-ophitic pale-brown augite, and a mesostasis of micropegmatitic quartz and feldspar.

To the west of Mollinsburn, two offshoots of quartz-dolerite extend north-westwards from the main, northern dyke, one between the Lyoncross and Orchard limestones just west of Mollin Craig (NS 711 718) and one 2 km farther west (NS 695 717). The dolerite was not encountered in workings below these outcrops, suggesting that they are portions of sills (Clough *et al.*, 1925). To the east of Mollinsburn, at North Medrox (NS 726 716), the dyke appears to be continuous with a sill on its south side, above the Calmy Limestone.

Evidence of the relationship between the intrusions and faulting is seen in other sectors of the Lenzie–Torphichen Dyke. Between Millersneuk (NS 665 718) and NS 695 717, just to the west of the GCR site, the dyke coincides with a major E–W-trending fault (the Annathill Fault). There, dark mudstones, thin coals and sandstones of the Lower Coal Measures are tilted up vertically against the northern wall of the dyke, whereas horizontal beds of indurated sandstone of the Passage Formation abut the southern margin. The dyke has been altered to 'white trap' up to 3 m inwards from both contacts. Some 25 km farther to the east, in the Torphichen district (around NS 970 720), the dyke is also emplaced along fault planes. The main sill in this area occurs in the Upper Limestone Formation on the north side of the fault but the only sill to the south of the fault occurs at much higher stratigraphical levels, in the Lower Coal Measures. Unfortunately the sill

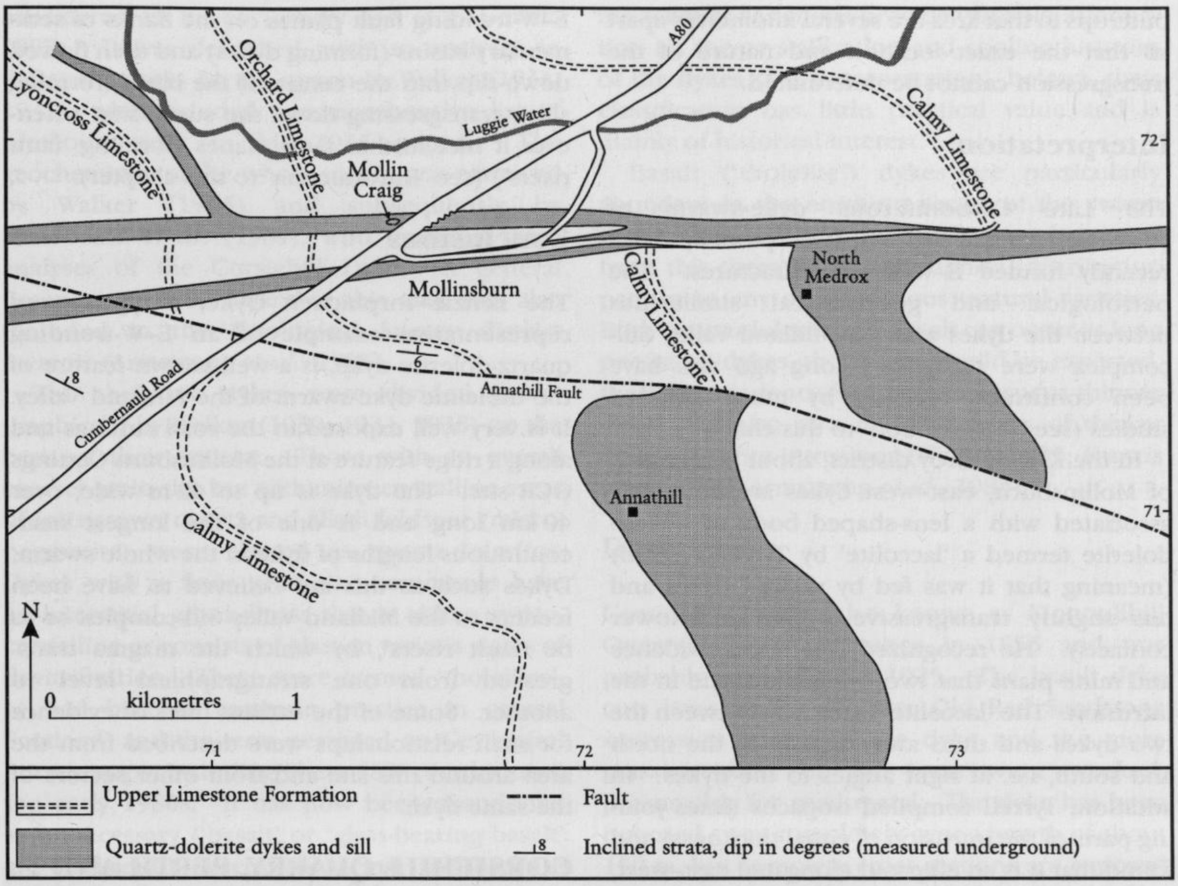

Figure 6.18 Map of the area around the Mollinsburn Cuttings GCR site. Based on British Geological Survey 1:10 000 Sheet NS 77 SW (1987).

Figure 6.19 E–W-trending quartz-dolerite dyke exhibiting good horizontal columnar jointing at Mollin Craig, Mollinsburn Cuttings GCR site. (Photo: C. MacFadyen.)

outcrops in that area are several kilometres apart so that the exact location and nature of the transgression cannot be determined.

Interpretation

The Late Carboniferous dyke-swarm of southern Scotland was emplaced partially along recently formed E–W-trending fractures. The petrological and geochemical similarities between the dykes and the Midland Valley Sill-complex were recognized long ago and have been confirmed recently by more detailed studies (see 'Introduction' to this chapter).

In the Kilsyth–Croy district, about 5 km north of Mollinsburn, east–west dykes are intimately associated with a lens-shaped body of quartz-dolerite termed a 'laccolite' by Tyrrell (1909b) (meaning that it was fed by vertical dykes and has slightly transgressive upper and lower contacts). He recognized from field evidence and mine plans that two dykes terminate in the intrusion. The 'laccolite' is thickest between the two dykes and thins away rapidly to the north and south, i.e. at right angles to the dykes. In addition, Tyrrell compiled isopachs (lines joining parts of the intrusion of equal thickness) and found that it is an ellipsoid elongated east–west, parallel to the dykes. Based on this evidence he suggested that the dykes were feeders to the intrusion. Evidence that the Lenzie–Torphichen Dyke is also a feeder to the sill-complex was revealed by Clough *et al.* (1925) when they described one of the offshoots of quartz-dolerite in the Mollinsburn district.

Peach *et al.* (1910) were the first to recognize the transgression of the sill-complex in the Torphichen district. In this area the Lenzie–Torphichen Dyke was described as a 'fault riser', meaning that emplacement was along a pre-existing fault plane. This provided a means for the sill-complex to transgress to different stratigraphical levels on either side of the fault along which it is emplaced. Similar relationships were interpreted by Clough *et al.* (1925) around Mollinsburn, and particularly good examples of transgression were described subsequently from the Stirling district (Dinham and Haldane, 1932; Francis *et al.*, 1970; see **Wallstale** GCR site report).

Early observations, such as these, all contributed to the overall model for the emplacement of the tholeiitic intrusions proposed by Francis (1982). In this model, magma rose along E–W-trending fault planes on the flanks of sedimentary basins (forming dykes) and then flowed down-dip into the centre of the basin (forming sills), transgressing down the succession whenever it met further fault planes (forming 'fault risers') (see 'Introduction' to this chapter).

Conclusions

The Lenzie–Torphichen Dyke, a typical and representative example of an E–W-trending quartz-dolerite dyke, is a well-known feature of the tholeiitic dyke-swarm of the Midland Valley. It is very well exposed in the road cuttings and along a ridge feature at the Mollinsburn Cuttings GCR site. The dyke is up to 40 m wide, over 40 km long and is one of the longest near-continuous lengths of dyke in the whole swarm. Dykes such as this are believed to have been feeders to the Midland Valley Sill-complex or to be 'fault risers', by which the magma transgressed from one stratigraphical level to another. Some of the earliest lines of evidence for such relationships were described from the area around this site and from other sectors of the same dyke.

CORSIEHILL QUARRY, PERTH AND KINROSS (NO 135 235)

D. Stephenson

Introduction

The extensive swarm of Late Carboniferous east- to ENE-trending tholeiitic basic dykes that crosses the Midland Valley and southern Highlands of Scotland is well represented in the area around Perth. The dykes have featured in several detailed accounts of the swarm and many have been used as type examples and are well known by name. One such dyke is the Corsiehill Dyke, which crops out on the northern slopes of Kinnoull Hill, 2 km to the east of Perth city centre. A complete cross-section of the dyke is well exposed in a disused quarry that has been converted into a car park for a local nature trail and is frequently visited for both educational and recreational purposes. The quarry is at the northern end of a larger SSSI that has been notified for its flora.

The dyke was shown on the first edition of the Geological Survey one-inch Sheet 48 (1883). At this time, all the E–W-trending dykes were considered to be of Tertiary age (e.g. Geikie, 1897). It was described, with an analysis, in definitive works on the swarm by Walker (1934, 1935), who included a comprehensive list of previous work in his 1935 paper. The geochemistry of the whole swarm was reviewed by Walker (1965) and subsequently by Macdonald *et al.* (1981), who included three analyses of the Corsiehill Dyke. A general description of the dykes in this area was also included in the Geological Survey district memoir (Armstrong *et al.*, 1985).

The tholeiitic dykes were divided petrographically by Walker (1930, 1934, 1935) on the basis of their texture. Those with an overall coarser grain-size but with microcrystalline areas of intergrown quartz and alkali feldspar (micropegmatite) were classed as quartz-dolerites. Dykes with a finer grain-size commonly have an interstitial groundmass that is either cryptocrystalline or consists of glass in various states of devitrification. These were termed 'tholeiites', as had become common practice in central Scotland, and the term persisted on Geological Survey maps, including Sheet 48W (Perth), until the early 1980s. It has now been abandoned as unnecessary ('basalt' or 'glass-bearing basalt' are sufficiently descriptive terms) and because of confusion with the term 'tholeiitic', which is now applied to magmas or suites of rocks defined by specific geochemical and mineralogical characteristics.

Walker further divided the 'tholeiites' into several named types, based mainly on the proportion and nature of the glassy groundmass. His 'Corsiehill' type is relatively coarse grained with only small areas of interstitial glass and grades into quartz-dolerite; other 'tholeiite' types are much more distinctive, with up to 20% of interstitial microlitic glass. However, more recent investigations (Stephenson in Armstrong *et al.*, 1985) have concluded that a spectrum of textures exists, from quartz-dolerite through the various types of 'tholeiite', and it is difficult to fit many individual rocks precisely into Walker's classification. All types share a common mineralogy in which similarities in mineral relationships outnumber the subtle differences, and Macdonald *et al.* (1981) identified no significant differences in geochemistry. Several dykes exhibit changes along their length through various 'tholeiite' types to quartz-dolerite and this close spatial relationship supports a genetic connection. Hence, although the textural variations provide valuable information on the crystallization and cooling histories of the dykes (see 'Interpretation', below), their classification has little practical value and is mainly of historical interest.

Basalt ('tholeiite') dykes are particularly abundant in the northern sector of the swarm that passes through the Perth area, but apart from this there is no geographical distribution pattern to any of the various textural varieties. Both quartz-dolerite and basalt can occur as long persistent dykes, though, as would be expected, there is a tendency for basalt to occur as thinner dykes and also as a marginal facies of thicker quartz-dolerite intrusions (Walker, 1935; Francis *et al.*, 1970; Armstrong *et al.*, 1985).

Description

Corsiehill Quarry (also known as Kinnoullhill Quarry) was in existence in 1855 and was probably worked until 1925. The basalt dyke cuts lavas within a Lower Old Red Sandstone succession and both the dyke and the more massive parts of the lavas were worked, presumably for road metal. The dyke has been quarried away completely over a length of about 150 m, but complete cross-sections are exposed at both the east and west ends of the quarry. The northern and southern quarry walls expose only lavas, apart from a thin skin of basalt at one point on the northern wall (Figure 6.20).

The lavas comprise the upper part of the Ochil Volcanic Formation on the northern limb of the Sidlaw Anticline, and form the dip-slope of Kinnoull Hill. They dip generally at about 10° to the north-west. They have a greyish-purple to greenish hue, contain conspicuous feldspar phenocrysts, with pyroxene, hornblende and biotite in the groundmass, and are probably basaltic andesites. They are amygdaloidal and commonly scoriaceous with large flattened vesicles, particularly on the northern side of the quarry. Collections of amygdaloidal material from the quarry in Perth Museum and Art Gallery include quartz, agate, amethyst, calcite, aragonite and chlorite. Acicular and hemispherical forms of goethite within quartz are particularly notable. Although visible contact effects due to the dyke are limited to minor baking, Shand (1908) noted the development of grossular garnet in lava adjacent to the dyke

The dyke trends east–west, like most others of the same swarm in the immediate area around

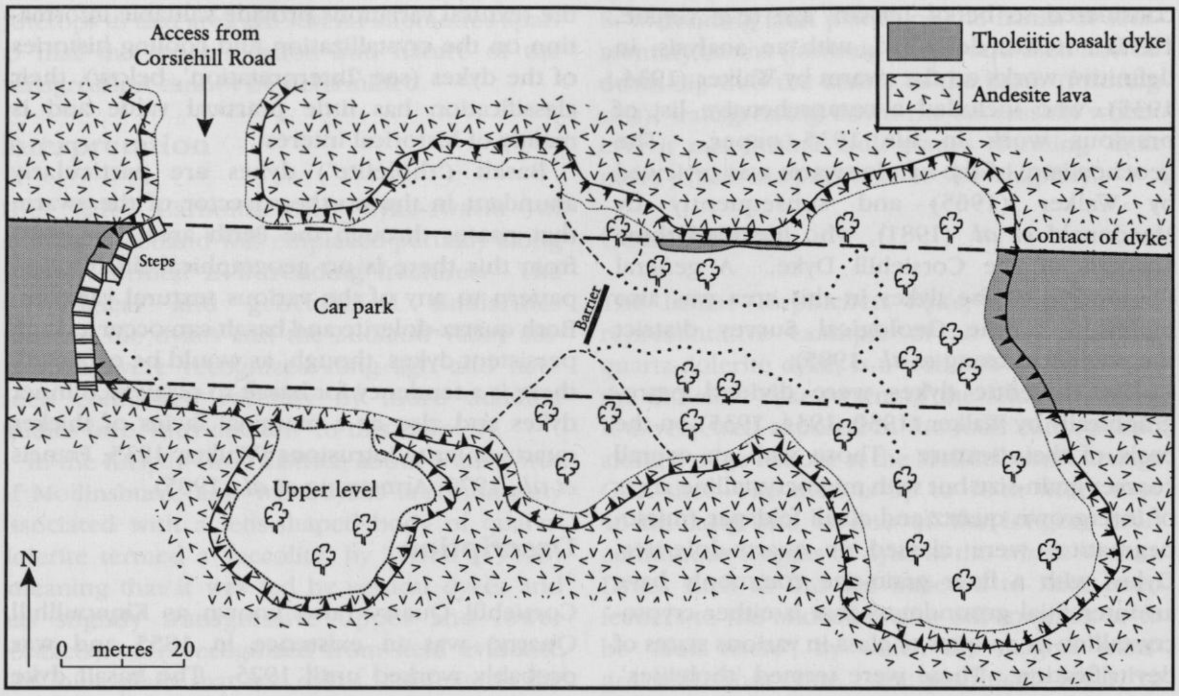

Figure 6.20 Map of the tholeiitic basalt dyke exposed in the Corsiehill Quarry GCR site. Adapted from an interpretive handout prepared by the Countryside Ranger Service, Perth and Kinross District Council (1990).

Perth, and can be traced for about 500 m. The contacts are vertical and the dyke is 20 m wide in the quarry. Both contacts can be observed at both ends of the quarry, where the dyke is seen to be chilled against baked lavas, and a thin skin of glassy basalt is preserved at one point on the northern quarry face. Joints perpendicular to the contact form crude hexagonal columns across the whole width of the dyke and these are the focus for well-developed spheroidal weathering that dominates the end walls of the quarry. The dyke is traversed by thin quartzo-feldspathic veins.

Despite the brown-weathering outer crust, the basalt is very fresh, particularly at the east end of the quarry. The rock varies from glassy to fine grained to medium grained, with plagioclase laths up to 2 mm long; the central part could be termed a dolerite. It comprises plagioclase (50%); subhedral to euhedral serpentine-carbonate pseudomorphs after early orthopyroxene and olivine (8%); sub-ophitic augite (30%); skeletal iron-titanium oxides (6%); and small amounts of interstitial microlitic glass (6%). Analyses show that it is quartz-hypersthene-normative with about 2% normative quartz.

Interpretation

The similarity of the basalts and quartz-dolerites of the dyke-swarm to the Midland Valley Sill-complex in all main aspects of geochemistry and petrography, and their close spatial relationships leave no doubt that they are comagmatic. The mantle origin and subsequent evolution of the high-Fe-Ti tholeiitic magmas was discussed by Macdonald *et al.* (1981) and is summarized in the 'Introduction' to this chapter. Individual dykes reveal only slight geochemical variation along their length, despite changes in texture, although fractionation is recorded between the margin and core of some thicker dykes and is noticeable in the three analyses from Corsiehill. Trace-element variation within individual dykes is much less than that observed between dykes so geochemical 'fingerprinting' is possible in some cases; however the Corsiehill Dyke is not particularly distinctive in this respect.

The basalt dykes of the swarm provide much useful petrological information that is not available from the coarser-grained quartz-dolerites. For instance, the early crystallizing phases such as olivine are preserved only in the finer-grained rocks, particularly in dyke margins, and the interstitial glass is a 'frozen' sample of the residuum that remains after the main phases have crystallized. The presence of residual Fe and Ti in this late liquid, a feature of tholeiitic magmas, is indicated by the abundance of ilmenite needles in the glass of many of the dykes. An analysis of glassy groundmass separated from a dyke near Kirkintilloch (Walker, 1935) demonstrates the high concentrations of SiO_2, K_2O and volatiles in the residuum. A few dykes have a tholeiitic andesite composition, but more evolved compositions occur only as aplitic veins and patches. These occur mainly in the associated sills but also in some of the thicker dykes and the Corsiehill Dyke is one of few where these can be observed.

The textural variations within the dyke-swarm that occur particularly in the area around Perth, were most likely induced by variations in the conditions of late-stage crystallization and cooling. Thus the glassy, quenched textures of many of the basalts ('tholeiites') contrast strongly with the interstitial crystalline intergrowths of the quartz-dolerites, which suggest slower cooling in the generally larger intrusions, possibly under the influence of trapped volatiles (see various GCR site reports describing the associated sills).

Conclusions

The Stephanian tholeiitic dyke-swarm that traverses central Scotland is dominated by medium-grained quartz-dolerites, but it also includes finer-grained basalts that are particularly abundant in the Perth area. At the Corsiehill Quarry GCR site one of these basalt dykes is particularly well displayed in a landscaped car park that serves a local nature trail. The 20 m-wide, E–W-trending dyke is intruded into lavas of Siluro–Devonian age that have yielded museum specimens of various minerals from infilled gas bubbles (amygdales). The chilled contacts of the dyke are well seen, as are horizontal columnar joints and spheroidal weathering, all in an ideal setting for demonstration to educational parties.

The basalt at Corsiehill Quarry is very fresh and consequently has been used in many microscopic and geochemical studies; it was the type example for a textural variety that formed part of a local classification of some historical interest. Like most of the basalt dykes in this swarm, it contains small areas of glass between the component crystals. These represent the liquid that remained after the magma had almost completely crystallized. It was 'frozen' as glass when the dyke rose rapidly through the Earth's crust and cooled very quickly. A study of this glassy material can yield much information about the nature of the original magma and its potential to evolve other, more fractionated magmas.

WHIN SILL EXPOSURES IN UPPER TEESDALE, COUNTY DURHAM High Force (NY 880 285–NY 885 286), Low Force (NY 903 281–NY 912 273), Falcon Clints (NY 815 285–NY 829 283), Cauldron Snout (NY 814 286), Cronkley Fell (NY 831 282–NY 854 282)

S.C. Loughlin

Introduction

Upper Teesdale contains a number of classic exposures of the Great Whin Sill, which combine textbook examples of features associated with sill intrusion with spectacular landscapes. The abundant features include the presence of baked sedimentary rocks at the upper and lower contacts of the sill, rafts of baked sedimentary rock within the sill, variations in grain size relating to cooling history, and transgressions where the sill changes level within the country-rock succession. Bands of very coarse-grained pegmatitic facies and felsic veins representing the final products of crystallization are well exposed. In places, joint and fracture surfaces are covered with the zeolite pectolite, which crystallized at a late stage in the cooling of the sill. There are also good examples of the bleached and altered sill-rock known as 'white whin', which is caused by the circulation of mineralizing fluids. The alteration of the sill by these fluids suggests that it pre-dates the northern Pennine mineralization. The Great Whin Sill is at its thickest (73 m) and occurs at its lowest stratigraphical level in Upper Teesdale. From here, the sill thins and rises in stratigraphical level in every direction, forming a 'saucer-shaped' intrusion (A.C. Dunham, 1970; Francis, 1982).

Upper Teesdale is a popular area for students and amateur geologists, which is reflected in the number of field guides and popular accounts of the area (e.g. A.C. Dunham, 1970; Johnson and K.C. Dunham in Johnson, 1973; Skipsey, 1992; Senior in Scrutton, 1995).

Description

The Teesdale Fault, which trends north-west–south-east along the upper part of Teesdale, has a downthrow to the north-east. Hence, to the south-west of the fault are the lowest Visean strata exposed in Teesdale, whereas to the north-east are strata that extend up through the Yoredale Series into the Namurian succession. The Great Whin Sill is here intruded into low stratigraphical levels, around the Melmerby Scar Limestone, and hence its outcrop is mostly restricted to the south-west side of the Teesdale Fault, where the valley sides are dominated by long crags of dolerite (Figure 6.21).

The margins of the Great Whin Sill are commonly fine grained and chilled, with a thin black skin that has commonly been described as glassy, although true glass may not be present. Moving away from the margins, the grain size increases to 2 mm (K.C. Dunham, 1948). Grain-size analyses have shown that the percentage of microphenocrysts increases towards the centre of the sill (Strasser-King, 1973; A.C. Dunham and Strasser-King, 1982). The quartz-dolerite of the main part of the sill is composed typically of 48% plagioclase, 29% clinopyroxene, 7% iron-titanium oxides with small amounts of orthopyroxene, pseudomorphs after olivine, chlorite, amphibole, carbonates, sulphides and apatite.

High Force

The spectacular waterfall of High Force (NY 880 284) cuts a classic section through the lower 7.3 m of the Great Whin Sill and the underlying sedimentary rocks. The waterfall lies at the head of a 300 m-long gorge in which the sill and associated sedimentary rocks are well exposed in the walls (Figure 6.22). The sill has strong vertical jointing giving a pseudo-columnar appearance to the rock. At the waterfall a sheet of dolerite is separated from the main sill by a thin raft of baked mudstone. The sill overlies baked sandstone and indurated mudstone and dark recrystallized fossiliferous carbonates of the Tyne Bottom Limestone; a good example of the contact with baked mudstone is exposed along the side of the path leading to the waterfall from the main road at High Force Hotel (NY 884 287). The section at High Force is as follows (thicknesses based on Clough, 1876):

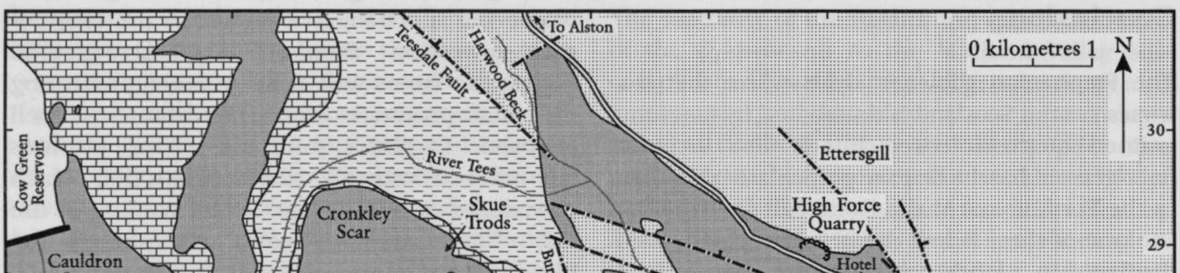

Figure 6.21 Map of the outcrops of the Great Whin Sill in the Upper Teesdale area. Based on Geological Survey 1:50 000 sheets 25, Alston (1965); and 31, Brough-under-Stainmore (1974).

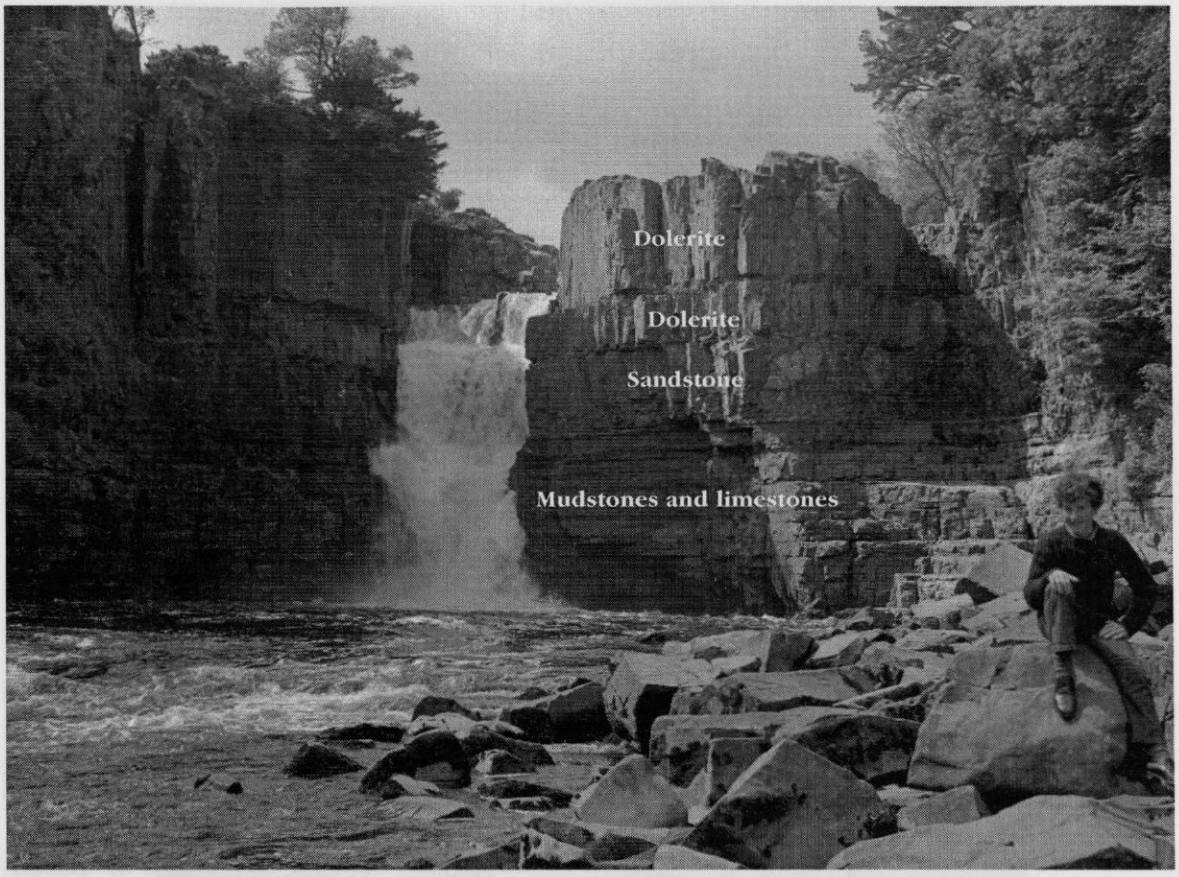

Figure 6.22 Quartz-dolerite of the Great Whin Sill (upper half of the cliff) at High Force, Upper Teesdale. The two highest layers of massive rock are dolerite, separated by a thin raft of baked sedimentary rock forming a plane of weakness near the top of the waterfall. Beneath is a thick bed of baked sandstone, resting upon well-bedded mudstones and limestones of the Tyne Bottom Limestone in the lower half of the cliff. (Photo: British Geological Survey, No. LFP00382, reproduced with the permission of the Director, British Geological Survey, © NERC.)

Dolerite (Great Whin Sill)	7.31 m
Altered mudstone	0.45 m
Dolerite sill	1.82 m
Baked sandstone	3.65 m
Mudstones and limestones (Tyne Bottom Limestone)	9.75 m

High Force Quarry (NY 879 290) (also known as 'Hargreaves Quarry') lies 400 m WNW of the High Force Hotel and provides an excellent section through the central and upper part of the Great Whin Sill. Based on evidence from borings around Ettersgill (NY 882 299), the sill is about 70 m thick at this locality (K.C. Dunham, 1948). The quarry faces reveal considerable variations in grain size and excellent examples of coarsely pegmatitic quartz-dolerite within the 'normal' dark-grey quartz-dolerite. The pegmatitic facies occurs as flat-lying sheets up to 30 cm thick and is characterized by elongate, bladed crystals of black augite up to 50 mm long and smaller laths of plagioclase. Radiometric determinations on grains of baddelyite (ZrO_2) from the pegmatites at this quarry have yielded a weighted mean $^{206}Pb/^{238}U$ age of 297.04 ± 0.4 Ma (M.A. Hamilton and D.G. Pearson, pers. comm., 2002), the most precise date yet obtained from the Whin Sill-complex. Intersertal micropegmatite also occurs with accessory hornblende, biotite and chlorite. Some of the strong vertical joint faces are coated with chlorite, calcite and white radiating crystals of pectolite (a zeolite) up to 5 cm in length.

Low Force

Between Scoberry Bridge (NY 910 273) and Low Force (NY 903 277), the River Tees cuts an excellent section through Carboniferous sedimentary rocks down to the upper contact of the Great Whin Sill. The strata and the sill dip to the east or south-east at an angle just greater than the gradient of the river and hence a traverse upstream, to the north-west, is down the section. The Cockle Shell Limestone overlies sandstone, mudstone and then the Single Post Limestone, which has been baked and recrystallized to a soft, white, crystalline marble. Sandstones and mudstones beneath this limestone are also extensively altered and indurated. The upper contact of the sill is extremely sharp and it is well exposed along the north bank of the river.

Near the south-eastern end of the sill outcrop the dolerite has a bleached appearance where it has been altered to 'white whin' (see 'Introduction' to this chapter). The alteration has occurred around a series of thin anastomosing mineral veins, which, though barren within the sill, may be followed up through the succession and into an area of mineralization within the Single Post Limestone. The mineral veins and replacement deposits found here contain sphalerite, siderite and pyrite.

Farther upstream, just below Wynch Bridge (NY 904 279), a 74 m-long 'raft' of baked siltstone lies within the upper part of the sill, dipping at an angle of *c.* 20°. It is in sharp contact with the surrounding chilled dolerite. Low Force is a series of rapids where the river flows over columnar-jointed dolerite, just upstream from Wynch Bridge.

Cronkley Fell

On the south bank of the River Tees in Upper Teesdale, the Great Whin Sill forms a 3 km-long line of cliffs known as Cronkley Scar (NY 834 280–NY 852 285). At this location the sill is intruded in an irregular manner into the recrystallized Melmerby Scar Limestone near the base of the Carboniferous sequence, and a steeply inclined raft of saccharoidal limestone crops out within the dolerite at Skue Trods (NY 848 289). The upper contact of the sill is clearly exposed on the hill-top, where it transgresses from the Melmerby Scar Limestone up into the overlying Robinson Limestone, which is also thermally metamorphosed (NY 842 285). This excellent example of the transgressive nature of the sill contrasts with the very constant level of the sill a short distance to the east at Noon Hill (NY 861 271). At Noon Hill the sill passes almost unaffected through the Burtreeford Disturbance, an east-facing faulted monocline. Hence, to the east of the monocline it is above the Tynebottom Limestone, whereas to the west it intrudes much lower beds (i.e. the Melmerby Scar Limestone).

Falcon Clints and Cauldron Snout

Cow Green Reservoir covers the site of Cow Green Mine which worked extensive veins of galena and baryte. Small mineral veins occur throughout this area and many were worked until the 1950s. At Cauldron Snout (NY 814 286), just 300 m south-east of the reservoir dam, the River Tees cascades spectacularly down columnar-jointed crags formed from the main body of the Great Whin Sill (Figure 6.23). In addition to typical dolerite, layers of coarse pegmatitic dolerite may be observed and radiating aggregates of pectolite occur as coatings on joint surfaces.

The sill also forms a cliff known as 'Falcon Clints' (NY 816 284–NY 827 281), which extends for over 1 km along the north side of the Tees valley, to the east of Cauldron Snout. The basal contact of the sill with the recrystallized (sugary textured) limestone of the Melmerby Scar Limestone and the altered upper part of the Orton Group is clearly exposed close to the foot of the crags. The thermal alteration of the sedimentary rocks is pronounced in this area both above and below the sill and, on weathering, it generates a thin soil that supports the relict arctic alpine flora (e.g. *Gentiana verna*) for which the area is well known (Johnson *et al.*, 1971).

Interpretation

The earliest debate about the origins of the Whin Sill focused on the sections in Upper Teesdale, where it was widely believed that the sill is conformable with the surrounding sedimentary rocks (hence the term 'Whin Sill', see 'Introduction' to this chapter). Sedgwick (1827) provided very good evidence for the intrusive nature of the sill in Upper Teesdale but, because it appeared to follow almost the same stratigraphical

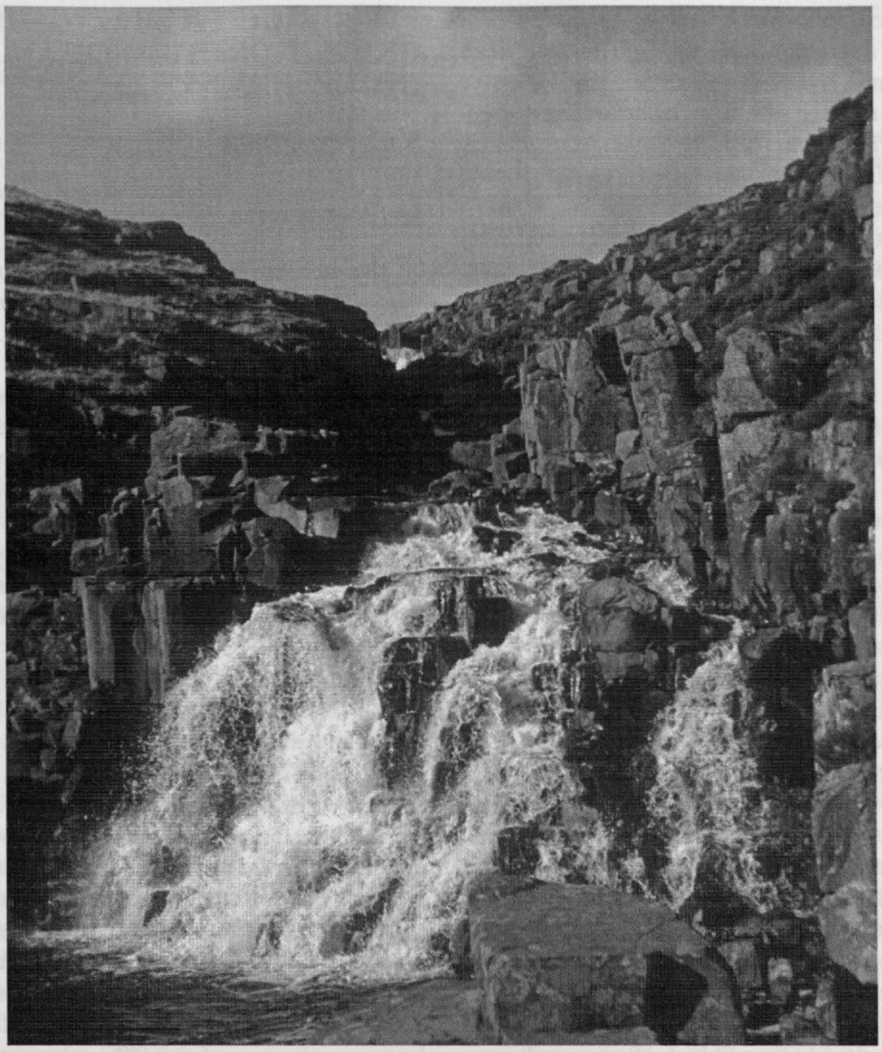

Figure 6.23 The Great Whin Sill exhibiting large-scale columnar jointing at Cauldron Snout, Upper Teesdale. (Photo: D. Stephenson.)

horizon throughout the area, there were those, especially within the mining community, who continued to doubt the evidence (e.g. Hutton, 1838). Phillips (1836) described the sill as a conformable bed, citing the High Force section as an example, but detailed work by the Geological Survey conclusively demonstrated the intrusive nature of the sill in Teesdale (Clough, 1876). Clough presented evidence that the sill is not conformable with underlying sedimentary rocks in the High Force section and also drew attention to the irregular nature of the basal contact, where apophyses of dolerite branch off from the main sill.

The field relationships revealed at this GCR site are now regarded as type examples of the features required to prove the intrusive character of a sheet of igneous rock. For example, thermally metamorphosed sedimentary rocks at both the lower and upper contacts are clearly demonstrated at High Force, Low Force and at Cronkley Scar. The fine-grained nature of the sill close to *both* contacts is evidence for rapid chilling of the intruded magma against a cooler host rock (columnar jointing is also an expression of cooling between two surfaces although it also commonly develops in lava flows). At a glance the Great Whin Sill does look conformable with the sedimentary rocks at several places in Upper Teesdale but closer inspection shows that most contacts are in fact transgressive; this is demonstrated extremely well at Cronkley Scar but also on a smaller scale at High Force. Both the upper and lower contacts are transgressive and the occurrence of blocks or rafts of sedimentary rock within the dolerite that have clearly detached from the overlying host rock provide further evidence for intrusion.

The Great Whin Sill attains its greatest known thickness of over 70 m in Upper Teesdale. Hence cooling was slow, possibly having taken about 60 years, according to A.C. Dunham and Kaye (1965). Several features can be attributed to the later stages of this slow cooling, such as the sheets of pegmatitic dolerite and felsic veins that are best seen in this area. The radiating growths of pectolite on joints are also considered to have formed during the late stages of cooling, as hydrothermal fluids circulated through the jointed rock (Wager, 1929a,b; Smythe, 1930a). The mineral veins that cut the sill near Low Force, altering it to 'white whin', are particularly significant because they prove that the sill was emplaced prior to the local mineralization event, which is part of the regional northern Pennine mineralization.

Conclusions

The Upper Teesdale GCR site provides a number of classic and scenic exposures of the Great Whin Sill, which demonstrate clearly most features associated with sill intrusion. The sill represents an extensive magma body intruded between layers of Lower Carboniferous sedimentary rocks. Outcrops reveal superb examples of chilled margins, thermally metamorphosed sedimentary rocks at upper and lower contacts, transgressive upper and lower contacts, rafts of baked roof material incorporated in the sill, and columnar jointing. This is the thickest part of the Great Whin Sill and excellent examples of very coarse-grained pegmatitic dolerite, formed during slow cooling, are exposed. A very precise radiometric date of 297.4 Ma has been obtained from this pegmatitic facies. During the late-stage cooling of the sill, hydrothermal fluids deposited the hydrous zeolite mineral pectolite on joint surfaces, and in places the fluids associated with mineral veins have altered the quartz-dolerite to 'white whin'. The latter relationship suggests that the widespread northern Pennine mineralization post-dated emplacement of the sill, which therefore provides a maximum age for this major ore-field.

STEEL RIGG TO SEWINGSHIELDS CRAGS, NORTHUMBERLAND (NY 751 676–NY 813 704)

S.C. Loughlin

Introduction

In the Roman Wall region, between Newcastle-upon-Tyne and Carlisle, the Great Whin Sill forms a spectacular north-facing scarp that extends for over 25 km to the north of the River South Tyne. The scarp forms a natural barrier that provided an ideal site for the construction of a substantial length of Hadrian's Wall and several important Roman forts (Figure 6.6). The area is one of outstanding natural beauty, is popular with walkers and rock-climbers and has been used as a major film location. It has been a recommended site for geological conservation since 1945 and is also included in the GCR for its Quaternary geology (Huddart and Glasser, 2002).

The Steel Rigg to Sewingshields Crags GCR site extends from the car park at Steel Rigg (NY 751 677), ENE for about 7 km to Sewingshields Crags (NY 810 703) (Figure 6.24). The quartz-dolerite sill is beautifully exposed in a series of crags over 30 m high and exhibits several fault-controlled transgressions between stratigraphical levels within the Visean sequence, well seen at Sewingshields Crags and Housesteads. At Sewingshields Crags there are good exposures of the chilled base and of the contact between the top of the sill and metamorphosed sedimentary rocks. There is also a large raft of baked limestone near the base of the sill.

The geology of the area was described briefly by Wallis (1769), Winch (1817) and Tate (1867, 1868) in their accounts of the geology of Northumberland. Baked sedimentary rocks above the sill in the Roman Wall area were important features in the summary of evidence by Topley and Lebour (1877) that finally established the intrusive origin of the sill. The Geological Survey mapped central and south Northumberland in the 1870s and six-inch sheets 106NE and 106SE were published in 1881. Smythe (1930a) described the transgression of the sill at this site in his extensive study of the geochemistry of the Whin Sill-complex. Further descriptions of the site and a detailed account of the Carboniferous rocks into which the sill is intruded were produced by Johnson (1959). A revision survey was completed by the

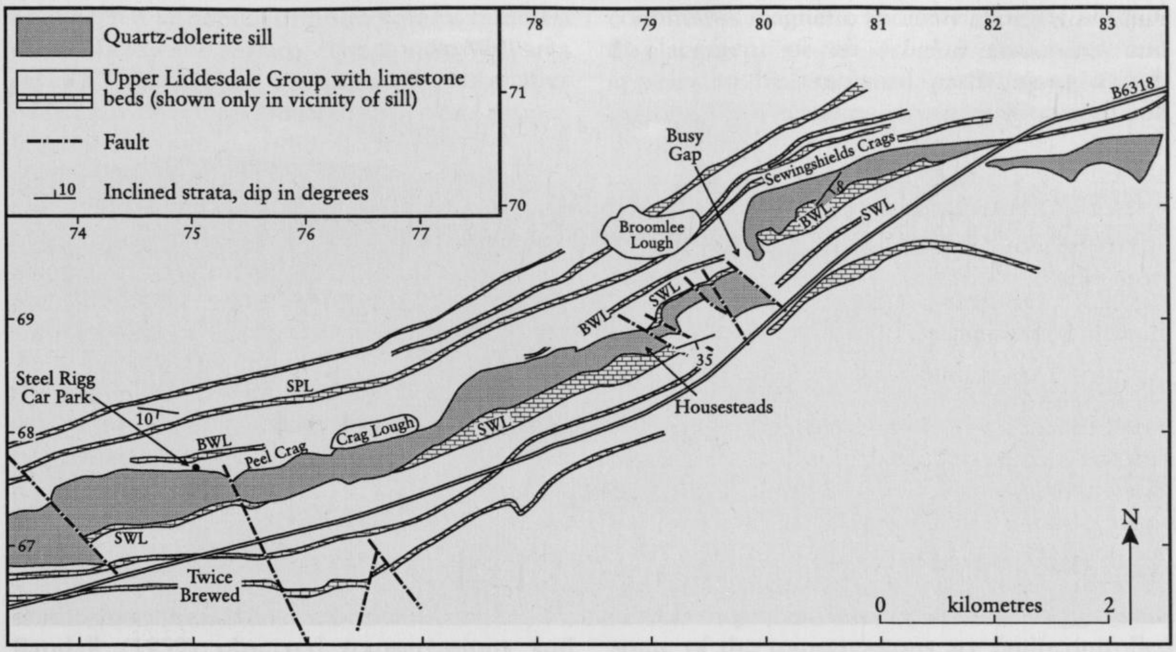

Figure 6.24 Map of the area around the Steel Rigg to Sewingshields Crags GCR site. (BWL = Bath-house Wood Limestone, SPL = Single Post Limestone, SWL = Shotto Wood Limestone.) After Johnson (1959).

Geological Survey in 1975 and 1:50 000 Sheet 13 (Bellingham) was published in 1980, together with a memoir (Frost and Holliday, 1980). The results of detailed ground magnetic surveys that clarify the structure of the sill at depth were described by Cornwell and Evans (1986). Descriptions are included in field guides of the area, including those by Jones (in Scrutton, 1995) and Johnson (1997).

Description

The north-facing scarp formed by the sill in this area is arguably the most impressive landscape feature of the whole Whin Sill-complex (Figure 6.25). At this site, and in adjacent areas, the scarp exhibits several offsets, which are caused by transgression of the sill between different levels within the Visean (Liddesdale Group) succession. In general, it is intruded at successively higher stratigraphical levels from east to west. Between the River North Tyne and Sharpley the sill is in the Oxford Limestone; between Carrowborough and Winshields (including this GCR site) it is among the Bath-house Wood and Shotto Wood limestones (it transgresses both up and down between them); and between Winshields and Greenhead the sill lies just below the Five Yard Limestone. The sedimentary rocks comprise repeated sequences of limestone, mudstone, siltstone, sandstone and coal deposited as Yoredale cycles.

Several transgressions occur close together within this GCR site. They appear to take place along small faults, which are visible in places as truncations in the sedimentary rock outcrops above the sill (Johnson, 1959), but are commonly hidden beneath thick drift deposits. In the western part of the site the sill is intruded into the Shotto Wood Limestone (Scar Limestone of Johnson, 1959). The sill and limestone form a composite dip-slope for several kilometres, along which vegetation on the differing rock-types contrasts sharply in colour and variety (Tate, 1868; Frost and Holliday, 1980). The sill escarpment is heavily indented, probably as a result of small faults that have fractured and shattered the dolerite. The most westerly indentation (NY 753 675) is quite deep and well defined. Several small transgressions take place around Housesteads (NY 790 688), where the sill moves to the top of the Shotto Wood Limestone. Farther east, at Busy Gap (NY 800 695), the sill abruptly changes horizon to the Bath-house Wood Limestone (Cockleshell Limestone of Johnson, 1959) and is offset several hundred metres to the north.

Figure 6.25 View of the north-facing crags of the Great Whin Sill from Steel Rigg. Peel Crag (nearest to camera), Crag Lough and Sewingshields Crags in the distance, are all topped by Hadrian's Wall. (Photo: British Geological Survey, No. L1555, reproduced with the permission of the Director, British Geological Survey, © NERC.)

The sill at this site is composed of homogenous quartz-dolerite with thin chilled margins at the top and base (less than 0.5 m). The thickness of the sill varies from 20 m to 50 m. It shows well-developed columnar jointing, particularly at Sewingshields Crags (NY 800 700) where isolated trapezoid pinnacles have been weathered out at the top of the crag. At Crag Lough and Peel Crag, the columns provide some of the most popular rock climbs in Northumberland. The upper and lower contacts of the sill are very well exposed at several locations within the site; for example, the Bath-house Wood Limestone rests directly on the sill at Sewingshields Crags, forming a composite dip-slope for several kilometres to the east. The contact metamorphism of the overlying sedimentary rocks is also particularly clear at Sewingshields Crags and a 2 m-thick raft of baked Bath-house Wood Limestone is exposed near the base of the sill at Sewingshields Castle (NY 8114 7041).

Alteration of the sill typically includes chloritization along joint planes and there are also some good examples of pectolitization. Pectolite (a zeolite) occurs at several places in the Whin Sill-complex but is particularly abundant in the vicinity of the Roman Wall. It generally takes the form of thin veins associated with calcite and also occurs in amygdales (Smythe, 1930a). These are surrounded by an aureole up to 1.5 cm wide of light-green altered dolerite in which further clusters of pectolite crystals can be observed. In other places amygdales comprise quartz and calcite.

Interpretation

The origin of the Whin Sill-complex was debated at length early in the 19th century. Early workers considered that it represented lava flows (e.g. Phillips, 1836; Hutton, 1838) but Tate (1867, 1868) recognized the evidence for intrusion in the vicinity of the Roman Wall, based on the metamorphism of the overlying strata. In their definitive discussion on the intrusive nature of the Whin Sill-complex, Topley and Lebour (1877) cited Sewingshields Crags as one of the better places to see evidence of contact metamorphism at the upper contact.

Since drift deposits at this site commonly cover areas crucial to the understanding of the sill transgression and its relationship to faulting, magnetic surveys have been used to work out the structure of the sill at depth. Strong magnetic anomalies occur along outcrops of the sill and also down-dip, where the intrusions can be detected at depths of up to several hundred metres below the surface. The Roman Wall area reveals numerous complicated anomalies which have been investigated by several groups (e.g. Summers *et al.*, 1982; Cornwell and Evans, 1986). These studies reveal clearly the segmented nature of the sill and, in a study of the Hexham area, Cornwell and Evans identified many magnetic lineaments, interpreted as faults or joints that are not necessarily visible at the surface. Based on magnetic evidence within this GCR site, the main offset at Busy Gap is seen to coincide with a NW-trending lineament that swings to the ESE about 4 km south of the outcrop. A major offset in the sill at Limestone Corner, 10 km to the east of the site, is controlled by a similar structure (Cornwell and Evans, 1986).

The relationship of the sill to faulting in the region has been of interest to many authors. In the adjacent area east of the River North Tyne, Randall (1959) observed transgressions and faulting but was unable to ascertain the exact age relationship, although he considered that the faults could not be younger than the intrusion. Johnson (1959) considered the transgressive steps at this GCR site to be fault-controlled. The predominant fault trend in the region is ENE, with a secondary ESE trend. These have been interpreted as conjugate shears formed during a period of E–W-trending compression, after the main north–south Variscan compression, but before intrusion of the Whin Sill-complex (Frost and Holliday, 1980). However, Frost and Holliday also suggested that the faulting and intrusion could be contemporaneous. Cornwell and Evans (1986) interpreted the segmented nature of the sill in this region as evidence of fault and/or joint control on the form of the intrusion. They were unable to determine the age of faulting from magnetic evidence but considered it probable that a major component was in existence at the time of intrusion. The minor indentations in the scarp suggest some faulting after emplacement of the sill and the largest indentation acted as a water channel which drained a lake to the north of the sill at the end of the last glaciation. Crag Lough is a remnant of this glacial lake, which formed in an ice-scoured basin (Johnson, 1997).

The St Oswald's Chapel Dyke, a member of the dyke-swarm associated with the sill-complex (Figure 6.2), crops out over a distance of several tens of kilometres, sub-parallel to the outcrop of the sill and about 5–7 km to the south. It has a continuous magnetic anomaly showing no fault displacement or *en échelon* structures and appears to be emplaced partly along a pre-existing WNW-trending structure (Cornwell and Evans, 1986).

Conclusions

The Steel Rigg to Sewingshields Crags GCR site demonstrates very well the dramatic effect that the Great Whin Sill has on the landscape, here forming a substantial north-facing scarp upon which Hadrian's Wall and several Roman forts were built. The scarp is offset at several places as a result of transgression of the sill between different levels within the sedimentary succession of the Visean Liddesdale Group. These transgressions have been the subject of much discussion, as the role of faulting is not always clear. Geophysical methods tend to suggest that some of the transgressions are fault-controlled and that magma moved along pre-existing fault zones. Small later faults cut the sill forming minor indentations in the outcrop; one of these acted as a channel when water drained from a glacial lake on the north side of the scarp at the end of the last glaciation.

The site was important during the early debate on the origins of the Whin Sill as it provides abundant evidence of the contact metamorphism of overlying sedimentary rocks, thus proving that it is an intrusion and not a lava flow. Other features of this site, typical of sills in general, include a large raft of baked limestone near the base of the sill and well-developed columnar jointing.

LONGHOUGHTON QUARRY, NORTHUMBERLAND (NU 231 153)

S.C. Loughlin

Introduction

Longhoughton Quarry, 4 km north-east of Alnwick in Northumberland, is located at the western end of a number of quarries collectively known as 'Howlet Hill Quarry', which were formerly worked for sets and road metal (Figure 6.26). It provides an excellent example of the thermal metamorphism of sedimentary rocks overlying the Great Whin Sill. The chilled upper surface of the sill is clearly exposed in the quarry and baked rafts of sedimentary rock can be seen

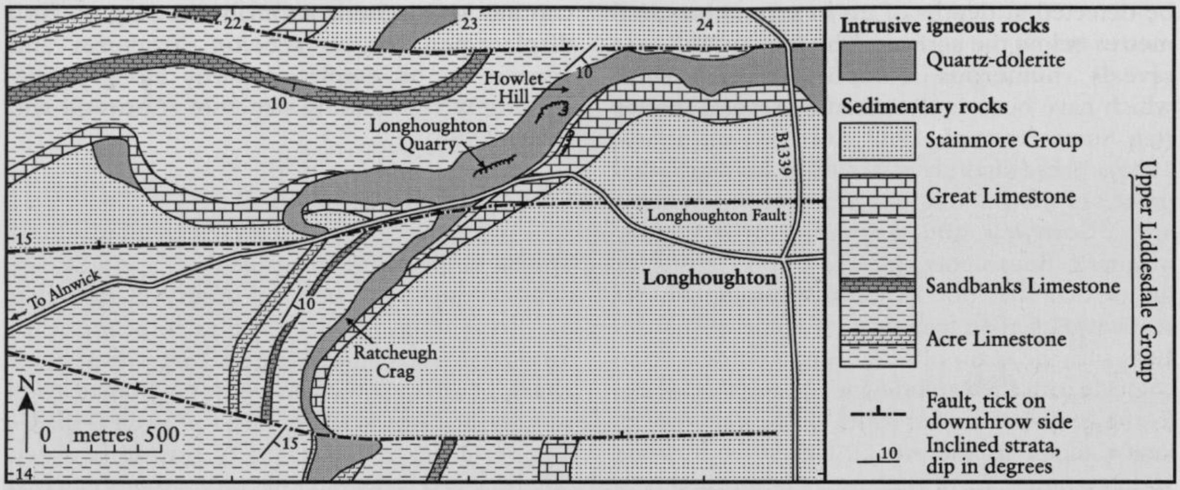

Figure 6.26 Map of the area around the Longhoughton Quarry GCR site. Based on Geological Survey 1:10 560 Sheet Northumberland 29SE (1926).

within the quartz-dolerite. The sill is intruded just below the (basal Namurian) Great Limestone at this site and nearby it cuts across two E–W-trending faults with no offset. This cross-cutting relationship provides evidence that the sill was intruded after the main movement on E–W-trending fractures in this area. However, shearing and slickensides within the dolerite imply that strike-slip movement also occurred after emplacement of the sill.

The area was first surveyed between 1860 and 1864 by the Geological Survey and, following revision of the six-inch maps in the 1920s, was published at the one-inch scale in 1930 as Sheet 6 (Alnwick). The quarries were described by Carruthers *et al.* (1930) in the memoir that accompanied the published map, and the timing of faulting and intrusion in this area was discussed by Jones *et al.* (1980), Turner *et al.* (1995) and Chadwick *et al.* (1995).

Description

A 20 m-high face at the north end of Longhoughton Quarry exposes the Great Whin Sill, which is intruded into sandstones and mudstones just below the Great Limestone. The overlying strata are thermally metamorphosed, and rafts of the overlying sandstones and mudstones, incorporated into the upper parts of the sill and prominent in this quarry, have been recrystallized. The chilled, fine-grained to glassy upper margin of the sill is exposed all along the eastern side of the workings. Just below the upper margin is a zone in which bands of small amygdales occur. The main part of the sill at this site is typical of the Great Whin Sill and has well-developed columnar jointing. It comprises homogeneous quartz-dolerite containing plagioclase, clinopyroxene, magnetite-ilmenite, quartz, orthopyroxene and small amounts of biotite, hornblende and carbonate. There is no evidence of a pegmatitic zone or segregation veins. A small fault at the western side of the quarry has exposed the basal margin and underlying indurated sandy mudstones. The basal contact can also be seen 300 m north-east of the summit of Howlet Hill, where thermally metamorphosed sandstones and mudstones are exposed at the base of a quartz-dolerite crag.

Just 0.5 km to the west of this GCR site the sill transgresses upwards through sandstones and mudstones and is intruded fully into the Great Limestone. A further 1 km to the west is an isolated outcrop of quartz-dolerite that was intruded above the Great Limestone.

Immediately to the south of the site, the sill cuts across the E–W-trending Longhoughton Fault with no apparent offset. The fault has undergone over 1.5 km of lateral movement (Carruthers *et al.*, 1930) although the Great Limestone outcrops on either side of the fault happen to coincide (Figure 6.26). Farther to the south, the sill crosses another E–W-trending fault, also with no offset, but to the south of this fault it intrudes the Acre Limestone, over 60 m lower in the succession. Horizontal slickensiding can be seen on some vertical surfaces of dolerite at Longhoughton Quarry and at nearby Ratcheugh Quarry. There is also evidence that the dolerite has been sheared.

Interpretation

Tate (1868) studied many outcrops of the Great Whin Sill throughout Northumberland and although Longhoughton Quarry was not so extensive at that time, he described the dolerite at nearby Ratcheugh Quarry as 'porphyritic' with large feldspar crystals scattered through the outcrop. His studies provided abundant evidence for the intrusive nature of the Great Whin Sill and led to a general acceptance. In particular, chilling of the upper margin of the sill, incorporation of rafts of the overlying sedimentary rock and thermal metamorphism of the overlying strata, all evidence of intrusion, are demonstrated in spectacular fashion at this GCR site.

The relationship of the Great Whin Sill to the Longhoughton Fault here shows that the sill post-dates the main fault movement. The sill cuts directly across the fault plane with no offset. Nevertheless, horizontal slickensides and shearing on some vertical faces in the quarries imply that there was also some late-stage strike-slip movement along related fractures *after* emplacement of the sill (Jones *et al.*, 1980). This is valuable evidence to add to that from elsewhere that E–W-trending faulting occurred before intrusion, such as quartz-dolerite dykes intruded locally along faults (see **Wydon** GCR site report) and transgression of the sill along fault planes (see **Steel Rigg to Sewingshields Crags** GCR site report).

Conclusions

The Longhoughton Quarry GCR site shows abundant features that prove the intrusive origin of the Great Whin Sill, such as the metamorphism of overlying strata, chilling of the upper margin and rafts incorporated from the overlying sedimentary strata. In addition, the relationship of the sill to the nearby Longhoughton Fault provides evidence relating to the sequence of events in northern England in Late Carboniferous times. The intrusion of the sill clearly post-dates the main movement on the E–W-trending fault, but shearing of the quartz-dolerite and the presence of horizontal slickensides on vertical rock faces show that there was also some strike-slip (lateral) movement after emplacement of the sill.

CULLERNOSE POINT TO CASTLE POINT, NORTHUMBERLAND (NU 260 187–NU 259 221)

S.C. Loughlin

Introduction

The Cullernose Point to Castle Point GCR site extends for 3.5 km along the Northumberland coast from the promontory of Castle Point south to Cullernose Point (Figure 6.27). The Great Whin Sill has a striking influence on the scenery in this area. The rocky promontory of Castle Point is the spectacular setting for Dunstanburgh Castle, and inland, 300–700 m from the coast, the sill crops out again to form a distinctive west-facing scarp that has been extensively quarried. A fault that cuts the sill forms the 'haven' of Craster and provides a natural harbour which was used to ship out the quarried stone. The picturesque Craster village is an excellent place to see the quartz-dolerite of the sill used as a building stone.

The sill is intruded immediately below the Great Limestone at the base of the Namurian Series, and both sedimentary rocks and sill dip gently eastwards. Cross-dip sections are well exposed at both the southern and northern margins of the GCR site, and along the intervening coastline the upper dip-slope is well exposed on the shore between tide marks. The excellent coastal exposures at Cullernose Point and at Castle Point clearly reveal the contact metamorphosed sedimentary rocks above and below the sill (Figures 6.28 and 6.29). Columnar jointing is well developed and there are blocks of baked sedimentary rock incorporated into the quartz-dolerite. Veins and pods of distinctive pink felsic material are particularly abundant near Cushat Shiel and this is perhaps the best site to observe such features in the Whin Sill-complex. It is also one of the best localities to observe evidence for later injections of basaltic magma into the sill.

A number of general papers on the geology of Northumberland with references to the Whin Sill at this GCR site were published in the 19th century (e.g. Winch, 1817; Tate, 1868). The most significant early paper was that of Tate (1871), which provided many illustrations of the intrusive nature of the sill in Northumberland. The intrusive nature was debated for several

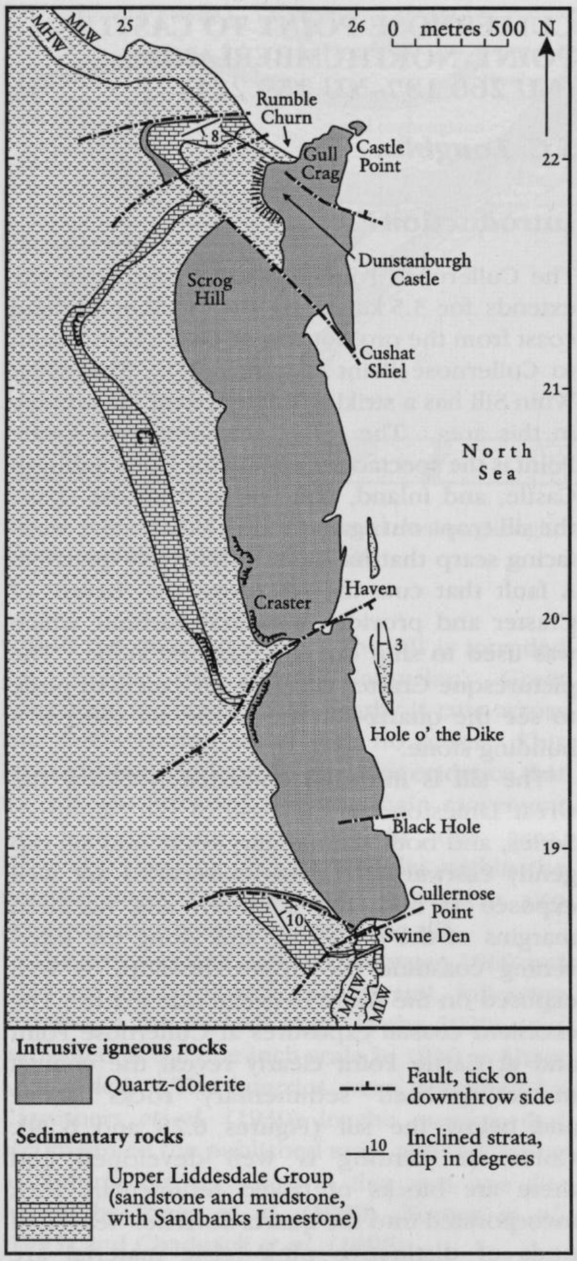

Figure 6.27 Map of the area around the Cullernose Point to Castle Point GCR site. Based on Geological Survey 1:63 360 Sheet 6, Alnwick (1930).

years until the abundant evidence was collated and presented by Topley and Lebour (1877). E.J. Garwood (in Bateson, 1895) presented a detailed account of the geology of this GCR site. The original geological survey of the Alnwick area was completed between 1871 and 1878 and the six-inch maps were revised between 1921 and 1925, leading to publication of the revised one-inch Sheet 6 (Alnwick) and an accompanying memoir (Carruthers *et al.*, 1930). The later basaltic intrusions and felsic veins and pods at this site were described and analysed by Smythe (1930a) in his paper on the geochemistry of the Whin Sill-complex.

Description

The Great Whin Sill is intruded below the Great Limestone into a sequence of mudstones, sandstones and limestones. Immediately to the north of Dunstanburgh Castle (NU 257 219), the sill and the underlying sedimentary rocks form the spectacular Gull Crag which comprises 16 m of columnar-jointed quartz-dolerite overlying 12 m of sandy mudstone and 2 m of grey and reddish-brown coarse sandstone. The latter is known as the Dunstanburgh Sandstone, which is distinctive because of the presence of abundant rounded clasts of quartz up to 3 mm in diameter. Contact metamorphism at the sill margins is confined to a narrow zone less than 0.5 m wide in which sandstones and limestones are recrystallized. The recrystallized limestones commonly contain pyrite, and mudstones typically become porcellanous. The main walls of Dunstanburgh Castle are made of the coarse, gritty Dunstanburgh Sandstone with a packing of quartz-dolerite boulders. The sill forms crags along the coastline for about 0.5 km south of the castle as far as Cushat Shiel (NW 259 213), a distinctive NW-trending slack that is the site of the Cushat Shiel Fault. The fault offsets the sill by almost 500 m to the west.

South of Cushat Shiel a number of faults intersect the coast, most of which have a trend of east–west or north-east–south-west. The upper surface of the sill is extremely well exposed on the shoreline between tide marks and shows the distinctive pattern of columnar joints perpendicular to the sill margins. At Craster (NW 259 200) a NE-trending fault cuts the sill, forming a natural harbour on the coast and a steep cleft in the escarpment west of the village. There has been very little movement on this structure since emplacement of the sill as the escarpment is not visibly offset. Between Scrog Hill (NW 254 214) and Craster the sill forms a steep west-facing escarpment cropping out 300–700 m inland and rising to a height of 35 m. This escarpment has been quarried extensively for both quartz-dolerite and the underlying Dunstanburgh Sandstone.

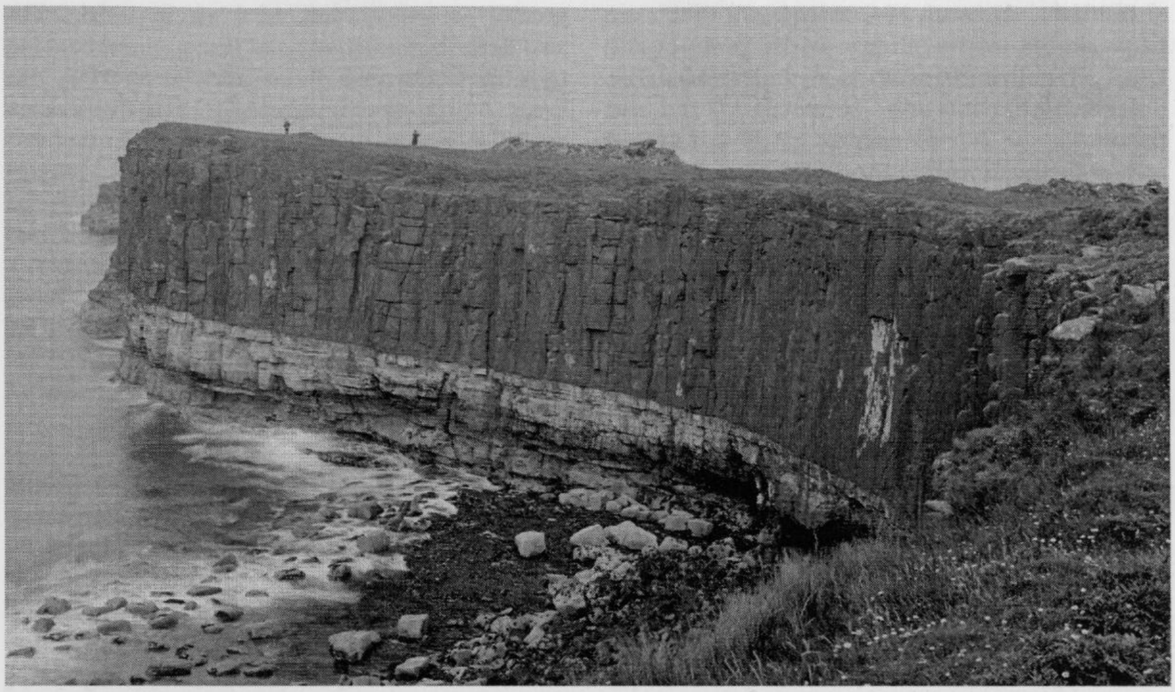

Figure 6.28 Columnar-jointed quartz-dolerite of the Great Whin Sill overlying sandstone at Castle Point. (Photo: British Geological Survey, No. A3077, reproduced with the permission of the Director, British Geological Survey, © NERC.)

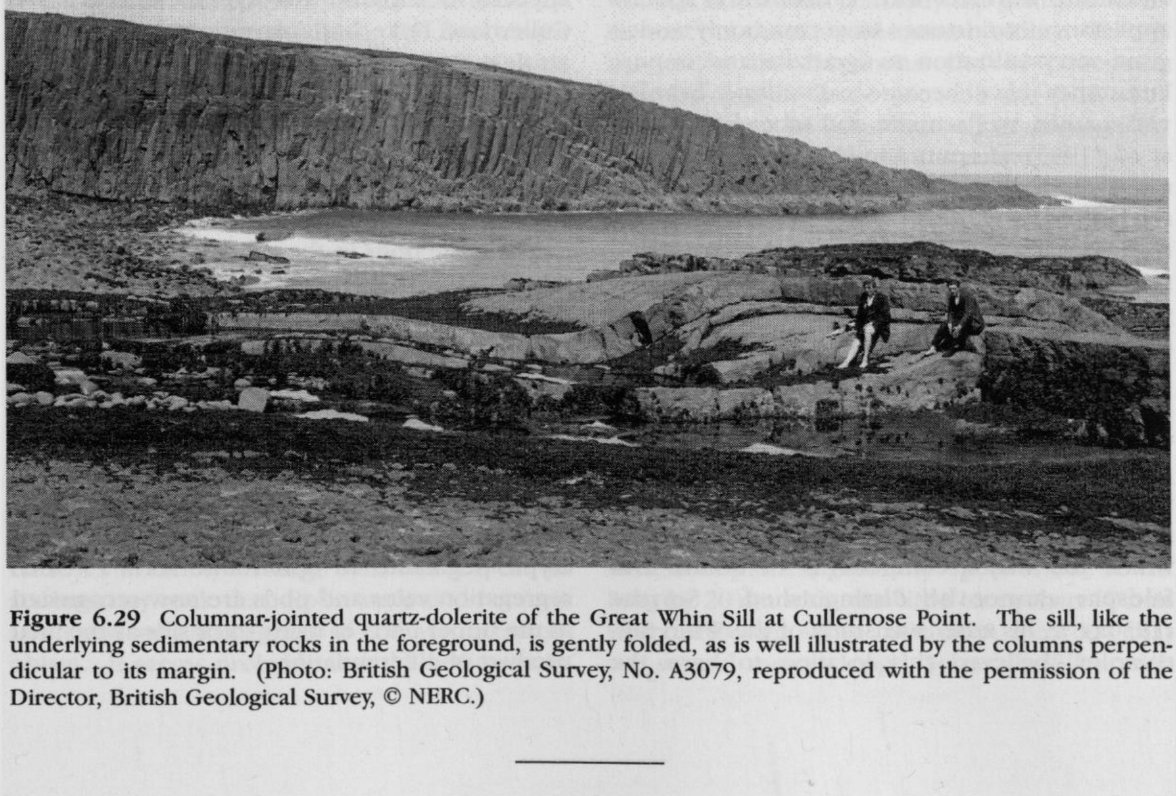

Figure 6.29 Columnar-jointed quartz-dolerite of the Great Whin Sill at Cullernose Point. The sill, like the underlying sedimentary rocks in the foreground, is gently folded, as is well illustrated by the columns perpendicular to its margin. (Photo: British Geological Survey, No. A3079, reproduced with the permission of the Director, British Geological Survey, © NERC.)

Immediately south of Craster is another zone of weakness in the sill known as 'Hole o' the Dike' which trends north-east–south-west. The dolerite within this zone is heavily jointed and there is some calcite veining. A few hundred metres farther south is another recessed feature known as 'Black Hole' (NW 261 191), which has a similar ENE–WSW orientation and is associated with fault-brecciated dolerite and extensive calcite veining. At the southern limit of the site is Cullernose Point (NW 261 187), a promontory rising to 20 m in height and composed entirely of columnar-jointed quartz-dolerite (Figure 6.29). This is a fine example of columnar jointing, with well-developed columns that are clearly perpendicular to the upper and lower margins of the sill. Just west of Cullernose Point at Swine Den, there are some spectacular xenoliths of Dunstanburgh Sandstone and mudstone within the sill (Smythe, 1931) and a few metres south of the main sill outcrop is a vertical quartz-dolerite dyke intruded into a fault. Xenoliths of fault-breccia can be observed within the dyke.

Xenoliths of country rock are also common in the sill in the vicinity of Dunstanburgh Castle and just north of the castle at Rumble Churn (Garwood in Bateson, 1895). The xenoliths of sandstone, mudstone and limestone are strongly affected by contact metamorphism. Mudstones have been converted to biotite-andalusite hornfels with a distinctive spotted appearance; sandstones have commonly undergone recrystallization to quartzite and impure limestones have become calc-silicate hornfels with garnet, wollastonite and idocrase (Westoll *et al.*, 1955). Impure limestones tend to show more alteration than pure limestones, as recognized by Randall (1959). Vesicles in the sill that are close to xenoliths commonly contain radiating crystals of quartz (in places amethysts), which are known locally as 'Dunstanburgh diamonds'.

Veins and pods of pink felsic material are particularly abundant around Cushat Shiel. The veins are up to 5 cm in width and the roundish pods are about 2 cm thick and several centimetres across. This felsic material varies in grain size from pegmatitic to cryptocrystalline in which the major components of quartz and feldspar cannot be distinguished. Smythe (1930a), in his extensive study of the Whin Sill-complex, believed this location to have the greatest concentration of felsic material. He also described intrusions of fine-grained basaltic rock at Cullernose Point and Scrog Hill, the latter being heavily altered. The intrusions are just a few centimetres thick and have chilled margins against the normal quartz-dolerite. The intrusion at Cullernose Point contains rare microphenocrysts of augite but is otherwise non-porphyritic. Smythe's analyses showed that these basic intrusions have broadly the same chemical composition as the sill.

Interpretation

Garwood (in Bateson, 1895) produced a field sketch showing the Cullernose Dyke at Swine Den feeding the sill, but Carruthers *et al.* (1930) were unable to find sufficient field evidence connecting the sill and the dyke. Westoll *et al.* (1955) discussed the emplacement of the Great Whin Sill in this area and described how it crosses pre-existing faults with little displacement but locally turns up or down a pre-existing fault zone to form transgressive connecting dykes between different stratigraphical or structural levels. They suggested that the Cullernose Dyke is an example of this process and the incorporation of inclusions of fault-breccia within the dyke proves the pre-existence of the fault. Magnetic evidence appears to support this hypothesis since the Cullernose Dyke has magnetic properties that are very similar to the Great Whin Sill (El-Harathi and Tarling, 1988) but different to the nearby Holy Island dyke system. This suggests that the Cullernose Dyke and the sill had a similar cooling history and may therefore have been emplaced contemporaneously.

The felsic pods in the vicinity of Cushat Shiel were described and analysed by Smythe (1930a). He concluded that as crystallization of the sill progressed, the remaining magma became progressively more acidic. The composition of this late-stage assemblage typically comprises small feldspar laths, some orthoclase and quartz. This assemblage forms either a relatively coarse-grained pegmatitic facies, an indeterminate fine-grained assemblage or, when concentrated, 'a crypto-pegmatite in spherulitic form'. Such segregation veins and pods are now recognized in the upper parts of many thick sills as the final product of differentiation.

The fine-grained basaltic intrusions, with chilled margins, are similar in composition to the sill and are therefore not differentiates. Smythe (1930a) argued that they must have been intruded later, 'at a time when the sill had become consolidated and cold'. This observation has potential significance in current debates concerning the relative ages of the sill-complex and the accompanying dyke-swarms.

Conclusions

At the Cullernose Point to Castle Point GCR site, excellent exposures reveal classic features relating to the intrusion and late-stage crystallization of a sill. In addition this site provides a spectacular example of the influence of the Great Whin Sill on the scenery of Northumberland, such as the high sea cliffs that were used as the foundations for Dunstanburgh Castle. The cliffs show well-developed columnar jointing and also contain large rafts of sedimentary rock incorporated during emplacement of the sill. These fragments of country rock are baked by the hot magma to form different metamorphic rocks depending on the composition of the original sedimentary rocks. Vesicles in the dolerite close to sandstone inclusions commonly contain radiating quartz crystals or amethyst and are known locally as 'Dunstanburgh diamonds'. In addition, the sill has abundant examples of quartz and feldspar-rich veins, which formed during the final stages of crystallization of the magma, and of later injections of basaltic magma.

BUDLE POINT TO HARKESS ROCKS, NORTHUMBERLAND (NU 163 361–NU 177 355)

S.C. Loughlin and D. Stephenson

Introduction

Coastal exposures to the west of Bamburgh village, Northumberland show the Great Whin Sill in extremely complicated contact with the host Carboniferous sedimentary rocks. At the Budle Point to Harkess Rocks GCR site, the sill encloses a variety of large rafts and blocks of sedimentary rock that dip in various directions and show varying degrees of contact metamorphism. It seems probable that the sedimentary beds were disrupted, perhaps by faulting, prior to intrusion of the sill. The basal and upper contacts of the sill are irregular and cut up and down the sedimentary succession throughout the site. At Budle Point the upper part of the sill is vesicular, with sinuous flow structures, suggesting that it was intruded at quite a shallow depth. Hydrothermal alteration has occurred close to ENE-trending veins that carry baryte and pyrite, and carbonate-filled fractures may indicate post-emplacement faulting.

This is the most complex of the GCR sites that represent the Whin Sill-complex. The extreme complexity has provoked much interest and many authors have attempted to describe and explain the relationships (e.g. Tate, 1868; Lebour and Fryer, 1877; Lebour, 1886; Carruthers *et al.*, 1927; Smythe, 1930b). Tate (1868) and other early authors described the outcrops but their field sketches were commonly stylized. Short descriptions of the exposures by Randall and Senior can be found in an excusion guide (Scrutton, 1995).

Description

Some 500 m north-west of Bamburgh Castle (NW 184 350) the Great Whin Sill is exposed on the foreshore for about 2 km between Harkess Rocks and Budle Point (Figure 6.30). The sill and the Carboniferous sedimentary rocks into which it is intruded generally dip gently towards the east but there is some minor folding. The sill lies above the Brigantian Oxford Limestone near Bamburgh Castle (outside the GCR site) where it can be seen cutting transgressively through cross-bedded red sandstones, but it lies close to the Budle Limestone at Budle Point (NW 163 361).

The shoreline is devoid of exposures for several hundred metres between Bamburgh Castle and Harkess Rocks, suggesting that the south-eastern margin of the rocks may be fault-controlled. At Harkess Rocks (NW 177 356) the sill is sub-horizontal and the upper chilled surface is exposed on the foreshore, the overlying sedimentary rocks having been completely removed by erosion (Figure 6.31). Close to the chilled surface is a zone of elongate and flattened vesicles, generally up to about 30 cm long by 20 cm wide and little more than 10 mm deep, although some have been recorded that are several metres long. Some are filled with

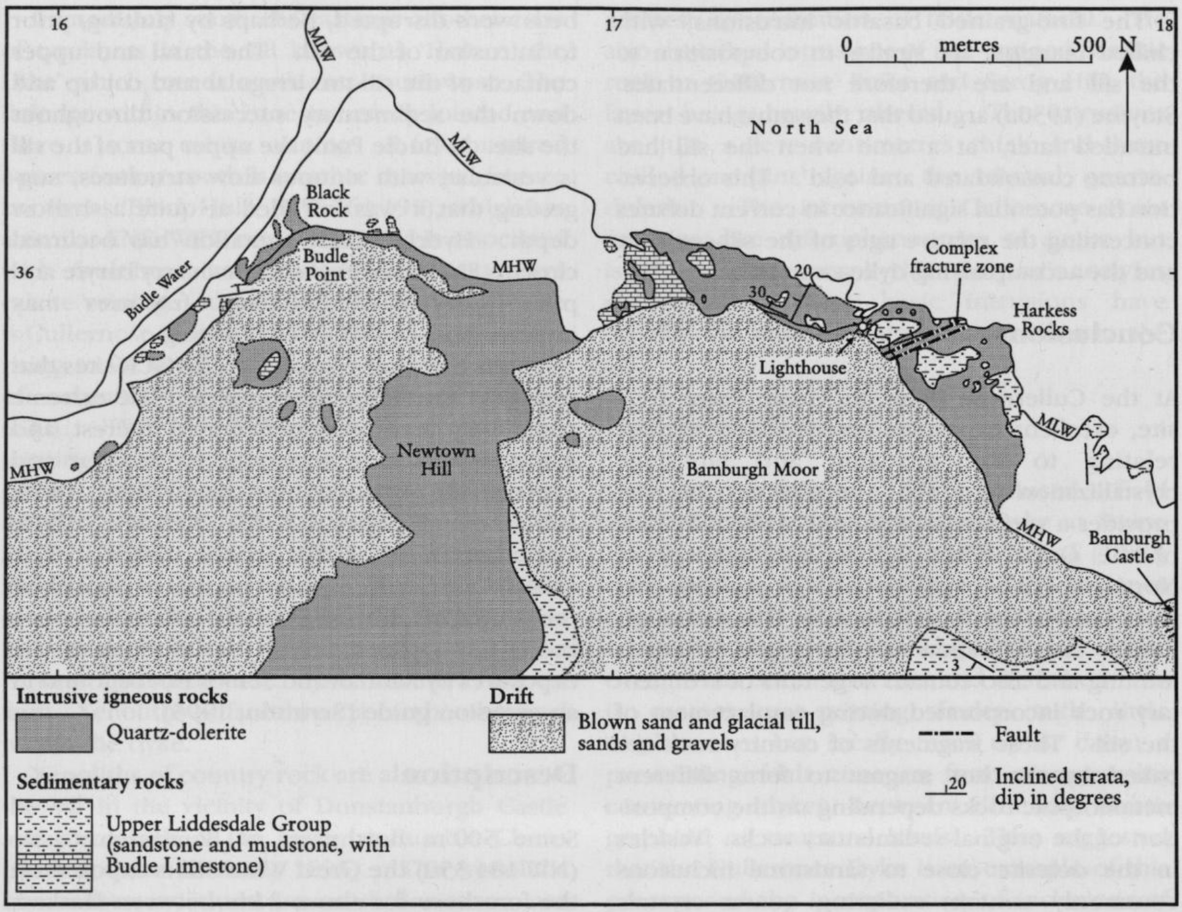

Figure 6.30 Map of the area around the Budle Point to Harkess Rocks GCR site. Based on Geological Survey 1:10 560 Sheet Northumberland, Old Series 16NE (1899).

quartz and a little calcite. Scattered about the sub-horizontal surfaces are areas of concentric curving ridges reminiscent of the surface patterns on pahoehoe lavas, but in miniature. These have been termed 'ropy flow structures' (Lebour and Fryer, 1877; Smythe, 1930b) and have been interpreted as having formed on the lower inside surfaces of the flattened vesicles. They have been exposed as the upper parts of the vesicles have been eroded away. Similar flow structures have been observed near to sub-horizontal contacts of the Holy Island intrusion (Randall and Farmer, 1970; see **Holy Island** GCR site report).

Large inclusions of sedimentary host rock occur within the quartz-dolerite throughout the Harkess Rocks area. Near the south-eastern edge of Harkess Rocks an inclusion of sandstone 11 m long dips steeply to the NNE. Farther to the north at the low-tide mark is a large mass of indurated mudstone, which extends for about 150 m and contains a dyke-like intrusion of quartz-dolerite, 16 m long. This mass of mudstone is surrounded by quartz-dolerite, but farther to the north and west small, thin skins of indurated mudstone lie directly on the fine-grained upper surface of the dolerite. The sill transgresses up through mudstone towards the north and numerous small mudstone inclusions may be observed within the quartz-dolerite along the shoreline.

Two ENE-trending fracture zones, about 25 m apart and with several splays, contain thin veins with baryte and pyrite in places. Between the two fracture zones is a chaotic zone of large blocks of sedimentary rock and irregular intrusions of dolerite. One block of white, rippled, fine-grained sandstone dips south-west at about 10° and just to the east of this, another mass of coarser sandstone dips east at about 60°. These

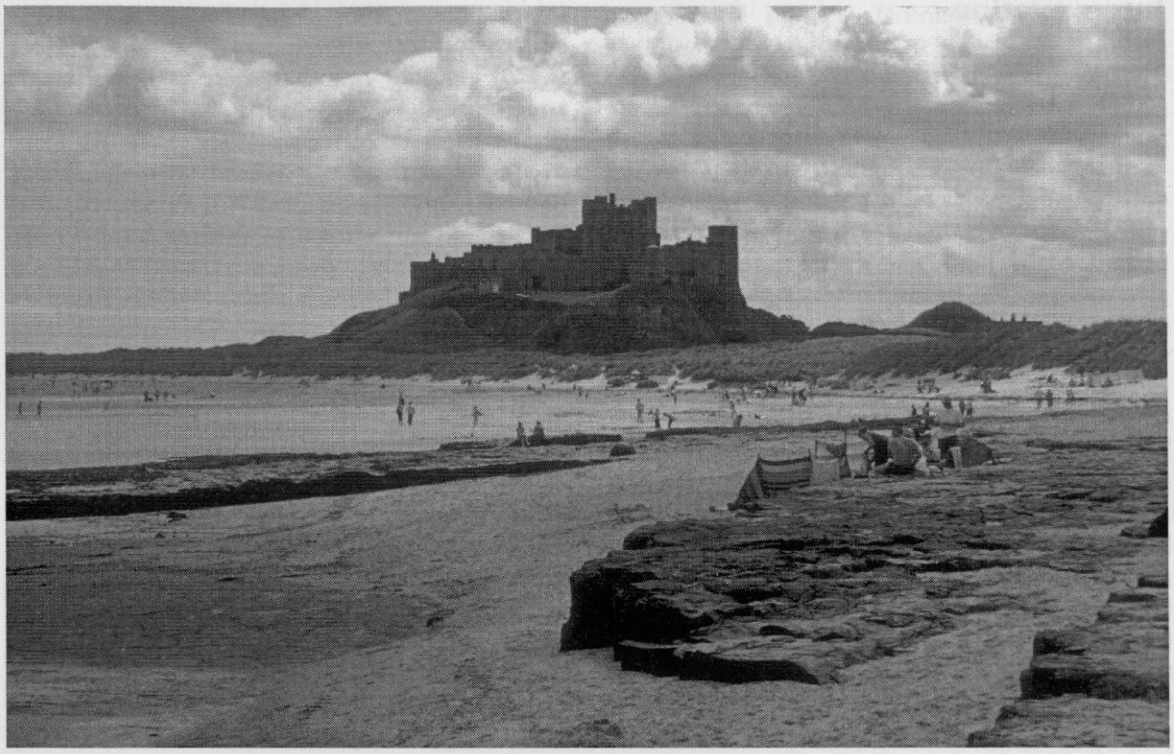

Figure 6.31 Bamburgh Castle, sited on a crag of quartz-dolerite of the Great Whin Sill, viewed from Harkess Rocks. The flat rocks in the foreground are close to the top surface of the sill; overlying sedimentary rocks have been removed completely, but the chilled margin of the sill is preserved as a thin skin in places. (Photo: D. Stephenson.)

sandstone bodies are clearly enclosed by quartz-dolerite. On the north side of the fracture zones, a thin bed of blue-grey recrystallized limestone dips NNW at about 30° and this is overlain by sandstone that crops out over a distance of about 30 m to the north to where it is overlain by the dolerite sill. The basal contact of the sill is magnificently exposed at the long low cliff extending to the ENE from the lighthouse and known as the Stag Rock (NW 175 359). The rocks here dip north-west at 10°–15° but curve around to dip just east of north at low-water mark. The contact transgresses the Budle Limestone and the immediately underlying and overlying mudstones and sandstones, cutting both up and down, usually in steps of 1–2 m along vertical joint or fault planes.

Near the lighthouse, the sill contains several rafts of varying size, up to 25 m long and 1 m thick, of blue-grey recrystallized limestone. In the vicinity of the larger rafts, the quartz-dolerite is cut by numerous thin carbonate-filled fractures. Further inclusions occur in the near-continuous exposures of dolerite that extend to the west of the lighthouse for at least 350 m. Most are irregular-shaped bodies of limestone and/or mudstone, with sharp angular outlines and varying in size from several centimetres to several metres. The dips of the bodies vary in direction and degree although there is a tendency towards northerly dips.

Near Budle Point the lower 1.5 m of the sill is amygdaloidal; the amygdales are typically calcite-filled. The sill overlies altered sandy mudstone, and west of Budle Point it terminates sharply against a NW-trending lineament, which is probably the line of a fault. West of this fault, irregular apophyses of dolerite can be seen protruding into almost flat-lying limestone, which extends for a further 200 m along the shoreline.

Some of the beach sands at Budle Bay are pinkish or purple in colour due to a high content of garnet (up to 45%). The garnets are thought to have been derived from Carboniferous age sandstones, where they are present as detrital grains (Hawkes and Smythe, 1931); they have no association with the sill.

Interpretation

The relationship between the sill and the host sedimentary rocks at the Budle Point to Harkess Rocks GCR site is extremely complicated, which is unusual for the Whin Sill-complex. This site and some locations on the Farne Islands are the only places where so many inclusions are observed, although rafts of sedimentary rock are also well exposed at the **Longhoughton Quarry** GCR site. The inclusions tend to be angular, with distinct, sharp margins, and show evidence of baking and alteration. This implies that they were fully lithified and disrupted before thermal metamorphism took place (e.g. Raymond and Murchison, 1988).

The large blocks of sedimentary rock between the ENE-trending fracture zones are enclosed within and intruded by dolerite, and it seems likely that these were broken up and disrupted by faulting prior to emplacement of the sill. To the immediate south of the fracture zones, the top surface of the exposure seems to be the top surface of the sill, as patches of chilled margin are preserved. However, to the north, a basal contact is exposed. Hence it appears that either the sill changed horizon along the pre-existing fracture zones or there has been a post-emplacement downthrow to the south on the bounding faults to the fracture zones. The total displacement must be of the order of several tens of metres (i.e. the full thickness of the sill) and it is possible that this is due to a combination of both mechanisms. Elsewhere, the sill is known to use pre-existing fault zones as 'risers' along which it transgressed to different stratigraphical levels (e.g. Smythe, 1930b; see **Cullernose Point to Castle Point** GCR site report) but there is also evidence that some faulting took place after emplacement.

The zones of elongate vesicles are also unusual in the Whin Sill-complex and the internal ropy flow surfaces are highly unusual, if not unique, worldwide. Lebour and Fryer (1877) considered them to be 'shrinkage or cooling marks in the shape of concentric ridges' but Smythe (1930b) suggested that they are 'the result of the slow flow of highly viscous liquid with a free surface'. Smythe considered that these structures are developed at four separate levels within the sill. He almost certainly got this impression as a result of the irregular upper surface of the sill, and Randall and Farmer (1970) pointed out that there is but a single zone, very close to the top. The structures are similar to those observed in short sill-like steps in a dyke at the **Holy Island** GCR site where Randall and Farmer (1970) suggested that emplacement occurred at shallow levels in the sedimentary pile, where vesicles formed as a result of rapid decompression and exsolution of volatiles from the magma. The vesicles then became flattened parallel to the contact and elongated in the flow direction. The linings of the vesicles began to cool before movement of the magma body had ceased and remained plastic long enough for flow structures to develop in them. Smythe (1930b) measured the elongation direction of the vesicles and the curvature of the ridges and deduced that the final movement of magma in the sill at Budle Point was from east to west, which is the opposite direction to that deduced for final movement in the Holy Island Dyke. Despite the fact that these are only local flow directions at the time of crystallization of the intrusive bodies, Randall and Farmer (1970) suggested that they cast doubt on the idea that the dykes and the Whin Sill were contemporaneous and that the dykes acted as feeders to the sill.

Conclusions

The Budle Point to Harkess Rocks GCR site is unique in the Whin Sill-complex because of the complexity of the relationship between the intrusion and the host sedimentary rocks. The rafts of sedimentary rock found within the intrusion are so numerous and of such diverse shape, size and orientation that it seems likely that the host rock was disrupted prior to intrusion. The angular, sharp margins of the inclusions show that the host rock was lithified prior to sill emplacement. Other features at this site include evidence of transgression of the sill and evidence of faulting after emplacement. Ropy flow surfaces on the inside of large elongate vesicles (gas cavities) near the top of the intrusion are an extremely rare, if not unique, feature worldwide and have been taken to imply emplacement at shallow depths. They suggest a magma flow direction from east to west.

GREENFOOT QUARRY, COUNTY DURHAM (NY 984 392)

S.C. Loughlin

Introduction

The abandoned Greenfoot Quarry, near Stanhope in Weardale, reveals the best available exposures of the distinctive Little Whin Sill, an important member of the Whin Sill-complex. This sill is intruded at a higher stratigraphical level than the Great Whin Sill, into the Upper Visean Three Yard Limestone, which has been slightly metasomatized at the contacts. Both the Little Whin Sill and the Great Whin Sill were intersected by the Rookhope Borehole, some 6 km north-west of the quarry; there the sills are about 130 m apart.

The Little Whin Sill was first described by Trevelyan as early as 1831. Clough (1880) suggested that the dolerite of the sill had assimilated the country rocks, and Egglestone (1910) described the field relationships in some detail. Principal descriptions of the petrography include those by Teall (1884a,b, 1888), Holmes and Smith (1921), Holmes and Harwood (1928), Tomkeieff (1929) and K.C. Dunham (1948). Geochemical studies by Smythe (1930a), A.C. Dunham and Kaye (1965) and Harrison (1968) have shown that the sill is similar to, but geochemically and mineralogically distinct from, other members of the Whin Sill-complex. It is the only intrusion in which fresh olivine phenocrysts have been found and may represent a more primitive parental magma to the complex (A.C. Dunham and Kaye, 1965; A.C. Dunham and Wilkinson, 1992).

Description

Greenfoot Quarry is situated 1 km west of Stanhope (Figure 6.32). The eastern end of the quarry is partially flooded obscuring the basal contact of the sill, but the upper contact is exposed all along the upper part of the south-facing quarry wall and is clearly visible from the Stanhope–Wearhead Road (A689). The sill is intruded into the Upper Visean Three Yard Limestone, which is about 2.5 m thick throughout Weardale. The west end of the quarry face reveals a complete section through the sill, with

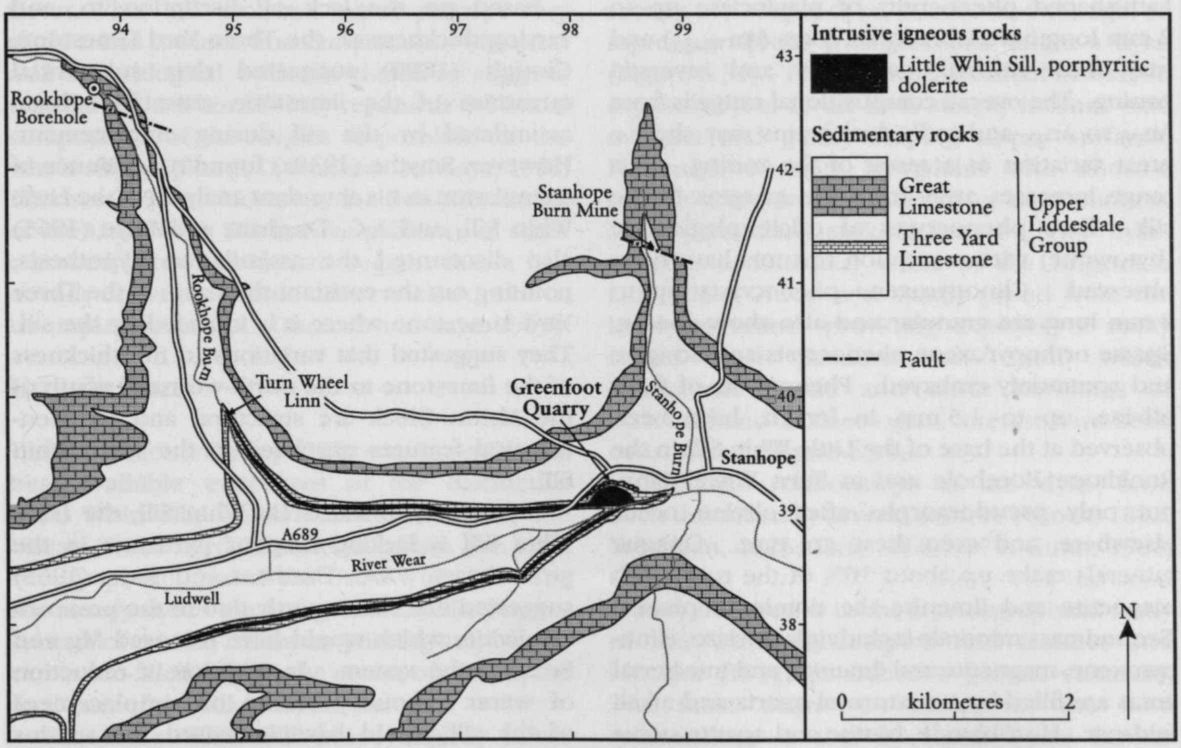

Figure 6.32 Map of the area around the Greenfoot Quarry GCR site. After A.C. Dunham and Kaye (1965).

metasomatized limestone above and below. The sill is 13 m thick and takes the form of a flat-lying sheet, with columnar jointing. This is the maximum known thickness of the Little Whin Sill, which thins westwards along the banks of the River Wear until it dies out in the vicinity of Ludwell (Figure 6.32). To the north, in the Rookhope Borehole (NY 937 427), the Little Whin Sill is about 2 m thick but it dies out rapidly to the west of Rookhope Burn. The sill has also been encountered to the north of the River Wear in Stotfield Burn Mine (NY 943 424) and Stanhope Burn Mine (NY 987 413). However, the absolute northern extent of the sill is unknown because mine workings and boreholes are too shallow to reach the northerly dipping Three Yard Limestone into which it is intruded. In the Woodland Borehole (NZ 091 277), some 15 km to the south-east of Stanhope, the Little Whin Sill is encountered 20 m above the Three Yard Limestone (Mills and Hull, 1968), but it is not present in outcrops in Upper Teesdale or in boreholes drilled to this level around Crook to the east.

The Little Whin Sill is a very fine- to fine-grained porphyritic dolerite. The grain size increases rapidly away from the chilled margins. Lath-shaped phenocrysts of plagioclase up to 2 mm long have labradorite cores (An_{70-68}) and may show normal, oscillatory and reversed zoning. The overall compositional range is from An_{70} to An_{35} and individual grains may show a great variation as a result of the zoning. This range increases away from the margins of the sill. Rare phenocrysts of calcic plagioclase (bytownite) with resorption textures have been observed. Clinopyroxene phenocrysts up to 2 mm long are granular and also show zoning. Sparse orthopyroxene phenocrysts are elongate and commonly embayed. Phenocrysts of fresh olivine, up to 1.5 mm in length, have been observed at the base of the Little Whin Sill in the Rookhope Borehole and at Turn Wheel Linn, but only pseudomorphs after olivine occur elsewhere, and even these are rare. Opaque minerals make up about 10% of the rock, with magnetite and ilmenite the dominant phases. Groundmass minerals include plagioclase, clinopyroxene, magnetite and ilmenite, and intersertal areas are filled by a mixture of quartz and alkali feldspar. Hornblende, biotite and apatite occur as accessory minerals, and pyrite and chalcopyrite have also been found at Greenfoot Quarry. In the central parts of the sill irregular vugs occur, containing quartz rimmed by carbonate (ankerite and calcite). In places, granular pyrite is associated with these vugs.

The Little Whin Sill has a relatively high total iron content but, in comparison to the Great Whin Sill, contains less silica (47%) and potassium. There is a detectable increase in the FeO/Fe_2O_3 ratio towards the centre of the sill, but other major elements and trace elements show little variation (A.C. Dunham and Kaye, 1965).

Interpretation

The first paper to concentrate on the Little Whin Sill described it as a basaltic lava (Trevelyan, 1831). At that time the Great Whin Sill was also considered by many to be a lava flow, despite the compelling evidence of intrusion presented by Sedgwick (1827), but the intrusive nature of the Whin Sill-complex as a whole was eventually recognized (Topley and Lebour, 1877). Topley and Lebour considered the two sills to be branches of one large intrusive sheet and Teall (1884a,b) showed that they are petrologically almost identical. Egglestone (1910) also proposed that they are contemporaneous.

Based on the lack of disruption to, and varying thickness of, the Three Yard Limestone, Clough (1880) suggested that substantial quantities of the limestone must have been assimilated by the sill during emplacement. However, Smythe (1930a) found no evidence of assimilation in his abundant analyses of the Little Whin Sill, and A.C. Dunham and Kaye (1965) also discounted the assimilation hypothesis, pointing out the constant thickness of the Three Yard Limestone where it is intruded by the sill. They suggested that variations in the thickness of the limestone to the north-west and south of the Alston Block are structural and sedimentological features unrelated to the Little Whin Sill.

In contrast to the Great Whin Sill, the Little Whin Sill is lacking Ca-poor pyroxene in the groundmass. A.C. Dunham and Kaye (1965) suggested that this is partly due to the presence of olivine, which would have removed Mg and Fe from the system. In addition, a reduction of water vapour pressure on emplacement of the sill would have increased the solidus temperature of the magma and therefore inhibited orthopyroxene crystallization. A.C.

Dunham and Kaye (1965) also investigated the apparent lack of crystal settling. They calculated that the Little Whin Sill in Greenfoot Quarry would have cooled in one and a half to two years (compared to 75 years for the Great Whin Sill at its thickest point) and they went on to suggest that rapid crystallization of microlytes impeded the settling of the phenocrysts. This process would also have inhibited circulation of the magma, thus explaining the zoning of the phenocrysts. The phenocrysts would have rapidly depleted their surrounding magma in Ca and Mg and hence the plagioclase crystallized with relatively Na-rich rims and the mafic minerals with Fe-rich rims. The centre of the Little Whin Sill, with its quartz-carbonate-filled vugs, was interpreted by A.C. Dunham and Kaye (1965) as the last zone to crystallize.

Geochemical analyses of all of the Whin Sill-complex samples plot between the alkaline and tholeiite fields on a silica–total alkali discrimination diagram and so may be described as transitional. Nevertheless the petrographical affinities are dominantly tholeiitic (A.C. Dunham and Kaye, 1965). When plotted on an AFM diagram, (Na_2O+K_2O)–FeO–MgO, the Little Whin Sill analyses form a tight cluster, in contrast to the Great Whin Sill analyses, which show a very slight trend towards iron enrichment. Chemical and mineralogical evidence therefore suggests that the Little Whin Sill may represent the initial composition of the magma responsible for the whole sill-complex (A.C. Dunham and Kaye, 1965; Harrison, 1968). However, the iron-rich nature of the Little Whin Sill and the presence of some resorbed bytownite crystals suggest that it had already undergone some differentiation prior to its emplacement (A.C. Dunham and Kaye, 1965).

Conclusions

The Greenfoot Quarry GCR site provides the best available exposures of the distinctive Little Whin Sill, which was intruded into the Visean Three Yard Limestone, above the local stratigraphical level of the Great Whin Sill. The site clearly shows the fine-grained, chilled upper contact of the sill, columnar jointing and quartz-carbonate-filled vugs in the centre of the sill, the final part of the sill to crystallize.

The Little Whin Sill has a slightly lower silica content than the Great Whin Sill and contains rare olivine phenocrysts. It is of great importance in understanding the origin of the Whin Sill-complex as a whole because it is thought to be close to the composition of the initial magma from which the complex evolved. However, a relatively high iron content and a rare occurrence of feldspar crystals that show signs of having reacted with the magma after they crystallized, suggest that the magma had already undergone some modification prior to emplacement.

HOLY ISLAND, NORTHUMBERLAND (NU 123 416–NU 149 419)

S.C. Loughlin and D. Stephenson

Introduction

The Holy Island coastal GCR site exhibits excellent exposures of a dyke system, related to the Whin Sill-complex, extending for over 30 km from Coldstream in the west to reefs off the east coast of Northumberland (Figure 6.2). Outcrops of quartz-dolerite extend for 2 km along the south coast of Holy Island between St Cuthbert's Isle and Scar Jockey rocks (Figure 6.33). These outcrops were formerly regarded as *en échelon* sectors of a simple dyke, but are now thought to represent sill-like transgressions within a dyke (Figure 6.34). They provide excellent accessible exposures that reveal both steeply inclined side margins and gently sloping upper surfaces. Flattened, elongate amygdales with unusual ropy flow textures on their lower inner surfaces are a particularly striking feature. The 'dyke' intrudes sedimentary rocks of the Brigantian Liddesdale Group and stands proud from the low-lying island, providing a series of rocky ridges and promontories upon which Lindisfarne Castle and other buildings of historical and archaeological interest have been constructed (Figure 6.35).

The field relationships of the 'dyke' have been described by several authors (Winch, 1822; Trevelyan, 1823; Tate, 1868, 1871; Gunn, 1900; Carruthers *et al.*, 1927). Holmes and Harwood (1928) included it in their petrographical study of the Whin Sill-complex and Holmes and Mockler (1931) produced a general summary. The most definitive account of the field relationships is that by Randall and Farmer (1970), who described the internal structure and the unusual flow textures in some detail. The

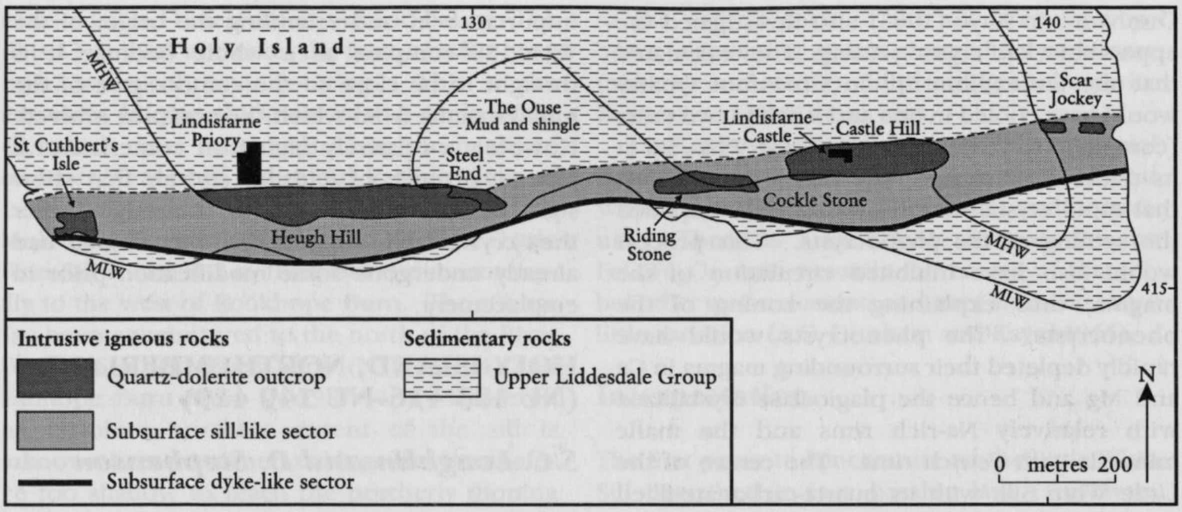

Figure 6.33 Map of the Holy Island GCR site. After Goulty *et al.* (2000).

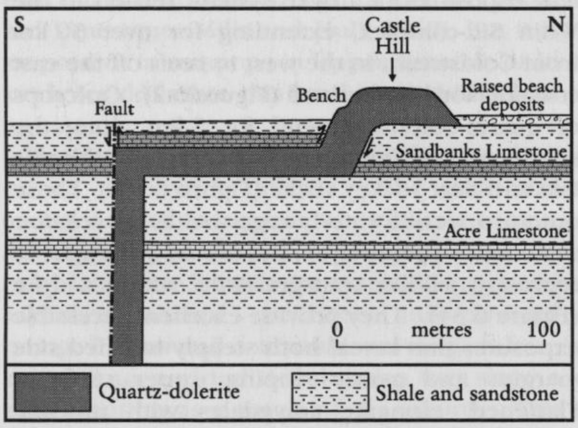

Figure 6.34 Sketch of a south–north section through the centre of Castle Hill, Holy Island, showing the alternating dyke-like and sill-like sectors of the intrusion. After Goulty *et al.* (2000).

intrusion was the subject of a palaeomagnetic study by Giddings *et al.* (1971) and a detailed magnetic survey of the mainland part of the dyke system was conducted by El-Harathi and Tarling (1988). However, it was the magnetic survey of Goulty *et al.* (2000) that revealed the most about the structure of the intrusion and resulted in a radical re-appraisal of its form. A weighted mean Ar-Ar age of 294 ± 2 Ma has recently been obtained from groundmass plagioclase in this intrusion (M. Timmerman, pers. comm., 2002). The 'dyke' is included in a field itinerary for Holy Island, described by Randall and Senior in the excursion guide of Scrutton (1995).

Description

The Holy Island Subswarm is the most northerly of the major dyke subswarms associated with the Great Whin Sill and is close to its northern limit (see **Budle Point to Harkess Rocks** GCR site report). In general, the mineralogy of the component dykes is the same as the sill, but the Holy Island 'Dyke' is porphyritic with phenocrysts of plagioclase, clinopyroxene and iron oxides in a fine-grained groundmass (Holmes and Harwood, 1928; Holmes and Mockler, 1931). On Holy Island itself there are five discrete *en échelon* outcrops, each of which has an east–west trend (Randall and Farmer, 1970). The outcrops reach a maximum width of *c.* 60 m but there is no northern contact exposed. The southern contact is undulating in places, but generally dips steeply to the south. The upper surface of each outcrop is generally irregular but in places it appears to be a planar margin to the intrusion, with a gentle dip to the east.

St Cuthbert's Isle

St Cuthbert's Isle (NW 123 416) is composed entirely of quartz-dolerite, having dominant sub-horizontal joints, and was interpreted by Goulty *et al.* (2000) as a sill-like body. Only the upper contact of the intrusion is exposed: in the eastern part of the isle the planar chilled surface dips gently to the east and the grain size of the rock increases downwards from this surface. The chilled margin contains a few microscopic

Figure 6.35 The south coast of Holy Island, clearly showing the overall apparent dyke-like nature of the quartz-dolerite intrusion, which provides the site for the castle in the far distance and shelters the priory in the middle distance. St Cuthbert's Isle, in the foreground, is formed from a sill-like step in the intrusion. (Photo: P. MacDonald.)

amygdales, but several centimetres lower there is a marked amygdaloidal zone, 15–23 cm thick, containing numerous flattened and elongate amygdales. The largest amygdales are several tens of centimetres across; they are flattened parallel to the chilled surface and are elongated towards the NNE. The amygdales comprise calcite, purple-tinted quartz and small amounts of chlorite. Where the filling has been removed by erosion the inner surfaces of the original vesicles can be seen. These are glassy, with tachylitic margins up to 2 mm thick. The lower inner surface of each vesicle has a ropy flow structure, similar (in miniature) to the ropy flow lobes on the surface of pahoehoe lava (Figure 6.36). The curvature on the flow lobes shows a fairly consistent flow direction to the east. These highly unusual features can also be seen near

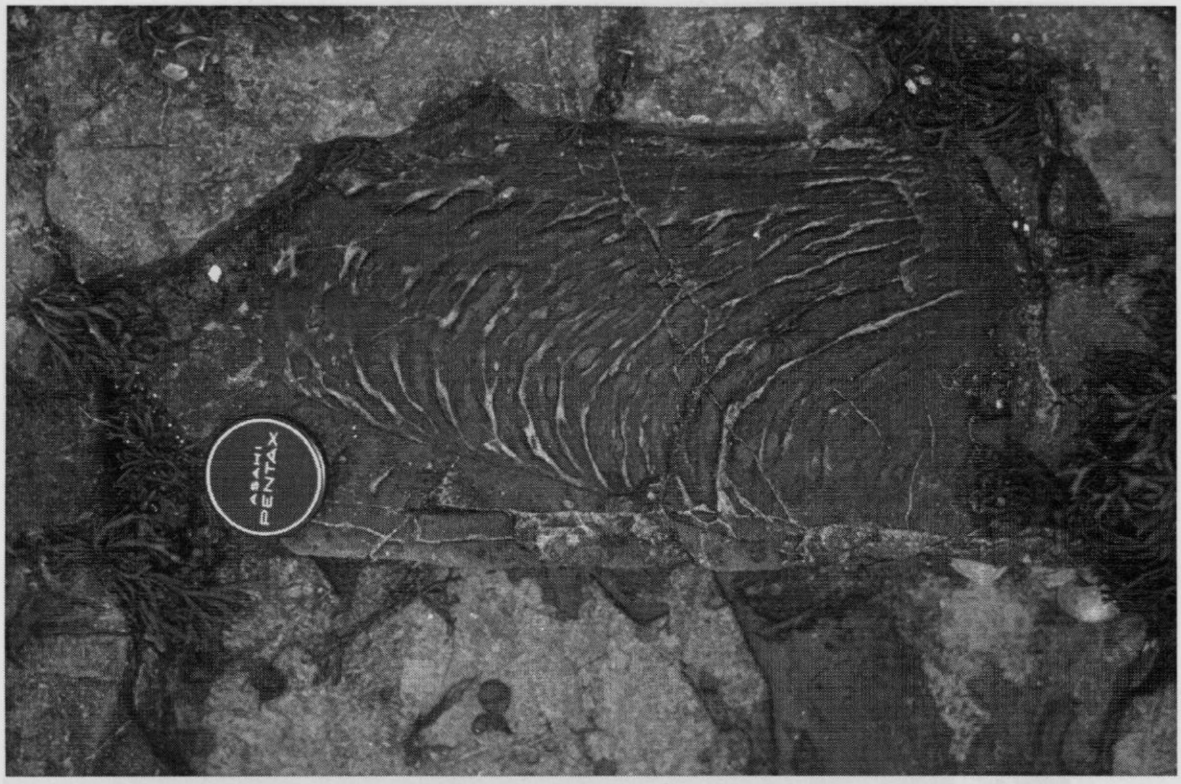

Figure 6.36 Ropy flow structure on the lower inner surface of a large flattened amygdaloidal cavity (the amygdaloidal 'fill' having been eroded away), St Cuthbert's Isle, Holy Island GCR site. The lens cap is 50 mm in diameter. (Photo: D. Stephenson.)

the top of the Great Whin Sill in the **Budle Point to Harkess Rocks** GCR site, 7 km to the south-east of here.

Immediately below this zone is a further amygdaloidal layer, about 0.8 m thick, in which the amygdales are small and spherical. This layer can be traced across much of the isle, suggesting that the upper surface of the intrusion was nowhere more than a metre or so above the current erosion surface.

Immediately to the south-east of the isle, a south-facing dolerite scarp, less than 1 m high and trending east–west, is exposed at low tide. This has been interpreted by Goulty *et al.* (2000) as the southern margin of a dyke, in continuity with the flat-lying sill that forms the main outcrop of St Cuthbert's Isle.

Heugh Hill

The Heugh Hill outcrop is up to 30 m across and extends some 500 m from the coast opposite St Cuthbert's Isle to the slipway at Steel End (NU 130 417). The sharp, steeply inclined southern contact is magnificently exposed almost continuously along the full length of the outcrop, but the northern contact is not exposed. The dominant cooling joints are almost vertical and perpendicular to the southern margin, but a strong joint set also occurs parallel to the margin. Marginal parts of the intrusion generally contain small spherical amygdales. Adjacent to the contact the Acre Limestone and overlying mudstones are both thermally metamorphosed. The limestone is recrystallized to a white marble, but in places fossils (corals, brachiopods and orthoceratids) are remarkably well preserved very close to the contact. The mudstone is baked and altered, with prominent dark 'spots' up to 2 cm in diameter, over a distance of about 5 m from the contact. Thin mineral veins and disseminated pyrite occur in this area. Xenoliths are common in the marginal part of the dolerite. Of particular note are three small rafts of saccharoidal limestone in the southern margin of the intrusion about 60 m from the western end of the outcrop, and a xenolith of baked mudstone just to the east of where the path across Heugh Hill emerges at the coast. Farther east, where the country-rock sandstone contains ferruginous nodules, some nodules seem to have been incorporated in the dyke margin. In the eastern parts of the outcrop, the southern contact is undulating and in places forms almost horizontal benches, below which flattened amygdales may be observed similar to those at St Cuthbert's Isle. The bench surfaces and the steeper contacts are coated with patchy 'skins' of sedimentary rock. At Steel End (NU 130 416), a smooth chilled surface is exposed at low tide that dips gently to the east. This surface reveals numerous clustered and elongated amygdales; abundant ropy flow structures are seen and the original quartz-calcite infills are better preserved than at St Cuthbert's Isle.

Castle Hill

The outcrop of dolerite at Castle Hill is almost 60 m wide. The undulating southern margin is exposed above the beach, where sub-horizontal sections form a series of benches, some up to 3 m wide. The most obvious bench, at Cockle Stone (NU 134 417), has the appearance of a man-made quay and has in fact been used as such. Thin skins of sedimentary rock coat the margin in places and flattened vesicles with ropy textured bases may be found on the benches. Curving cooling joints are parallel to the undulating contact. Near the castle a small offshoot from the main intrusion extends for 11.5 m into the surrounding mudstones. This apophysis is composed of 'white whin', dolerite altered by circulating mineral-rich fluids. The rock exposed below and to the east of the castle is vesicular and fine grained, with pervasive horizontal jointing.

Scar Jockey

At Scar Jockey dolerite crops out on the shoreline but no contacts are exposed. Prominent joints dip at 20° to the south-east and are typical of those along the northern margin of the other outcrops (Randall and Farmer, 1970).

Plough Rock and Goldstone Rock

The Plough Rock, 1 km from shore, is composed entirely of dolerite and marks the edge of a reef known as Plough Seat, which is partially visible at very low tides. Dolerite is further exposed 3.5 km offshore on the Goldstone Rock.

Interpretation

The igneous and intrusive nature of the 'dyke' at Holy Island was recognized by early authors (Winch, 1822; Trevelyan, 1823). On early one-inch-scale geological maps of the 1870s all the outcrops on Holy Island and further *en échelon* segments on the mainland were joined as one long sinuous dyke. Gunn (1900) recognized the discontinuous nature of the dyke and a revision of the six-inch maps took place during the 1920s (Carruthers *et al.*, 1927).

Holmes and Harwood (1928) suggested that the Holy Island 'Dyke' and its mainland equivalents were intruded into pre-existing tension cracks developed during a period of Late Carboniferous east–west compression, which was also responsible for the Holburn and Lemmington anticlines. This theory was accepted by many authors (e.g. Robson, 1954, 1977; Westoll *et al.*, 1955; Shiells, 1964; Wilson, 1970). However, Carruthers *et al.* (1927) noted field relationships suggesting that the dykes post-dated the compression event, and Jones *et al.* (1980) pointed out that the tension gashes occur between shear faults that offset the axis of the Holburn Anticline. The magnetic survey of El-Harathi and Tarling (1988) showed that there are four distinct sub-parallel ENE-trending dykes in the mainland part of the subswarm, rather than numerous small offset segments, and they interpreted this as proof that dyke emplacement was not related to an east–west compressional event. They suggested that the dykes represent the infilling of tensional fractures formed after the compressional event, perhaps during isostatic adjustment between the Cheviot Massif and the Northumberland Trough.

Giddings *et al.* (1971) proposed that at the time of crystallization of the Holy Island 'Dyke', the magnetic pole was at latitude 38° N and longitude 177° E. This is consistent with its formation close to the equator in latest Carboniferous or Early Permian times when the ancient geomagnetic field was reversed. This location is statistically indistinguishable from that determined for the Great Whin Sill by Creer *et al.* (1959). However, the recently obtained Ar-Ar date of 294 ± 2 Ma is significantly younger than the even more precise 297.4 ± 0.4 Ma U-Pb date from the Great Whin Sill (see **Upper Teesdale** GCR site report) and may re-inforce views that the sills and dykes are not quite coeval.

The steeply inclined, chilled southern contacts to the intrusion on Holy Island imply a dyke-like body, but several of the outcrops also exhibit planar chilled upper surfaces that dip gently to the east. Sub-horizontal jointing is dominant close to these contacts, increasing in intensity towards them, and parallel zones of flattened elongate amygdales also occur. The sub-horizontal contacts were originally interpreted as the upper termination of a dyke within the Carboniferous sedimentary pile (Randall and Farmer, 1970). Such a blunt termination is most unusual in dykes, which normally taper and pinch-out upwards, yet this interpretation persisted until a detailed magnetic survey by Goulty *et al.* (2000) suggested a form that fits the field observations much more convincingly (Figure 6.34). The magnetic survey suggests that most of the outcrops (Heugh Hill, Castle Hill and Scar Jockey) are formed from a sill that 'turns down' to the south to become a steeply inclined dyke. (The northern margin has been removed by erosion, so it is not known whether the sill continued farther to the north or whether it turned up within a short distance to continue as a dyke.) To the south of these outcrops, the intrusion levels out to form another sill-like sector, seen only on St Cuthbert's Isle. This then turns down to the south into a dyke, seen only in the small scarp south-east of the isle, but traced by its magnetic anomaly to the south of all of the outcrops (Figure 6.33). Although the sill-like sectors have a slight dip to the east, they must also step up to the east, as they transgress up through the stratigraphy of the host rocks in this direction. Hence the intrusion has the form of a step-and-stair transgression that steps upwards both to the north and to the east, though probably as part of an overall dyke-like body with only minor sill-like sectors. The overall form is in fact hinted at by the bench-like 'steps' that have long been recognized in the steep contacts on the southern margin of the main outcrops.

The sill-like parts of the intrusion are characterized by amygdaloidal zones in much the same way as a lava flow. The amygdales are infills of vesicles that formed by the exsolution of volatiles from the magma, probably following rapid decompression as a result of injection into the near-surface sedimentary pile. The rapid release of volatiles causes undercooling, which leads to rapid crystallization of the magma, hence explaining the fine-grained linings around the vesicles (Randall and Farmer, 1970). The quenched linings must have remained plastic for long enough to allow flattening, elongation and the development of flow structures by the still-molten magma moving through the intrusion. The flow structures at the base of the vesicles resemble pahoehoe ropy flow structures on the surface of lava flows and can be used to infer local flow directions (Figure 6.36). Randall and Farmer (1970) constructed rose diagrams from their field data to deduce the modal flow directions at three different localities. All three sites showed evidence that the final, local horizontal component of the flow direction was from west to east. The appearance of the flow structures is very similar to ropy flow structures described by Smythe (1930b) towards the top of the sub-horizontal Great Whin Sill at Harkess Rocks west of Bamburgh. There, the flow direction indicated by these structures suggests that final movement of magma in the Great Whin Sill was from east to west (see **Budle Point to Harkess Rocks** GCR site report).

Conclusions

The Holy Island 'Dyke' is an extremely well exposed component of an E–W-trending dyke system at the northern margin of, and related to, the Whin Sill-complex. The upstanding rocky ridge is a significant landscape feature that has clearly influenced the defensive and monastic settlements of Lindisfarne, one of the prime historical sites in Britain.

The exposures comprise several outcrops of quartz-dolerite that show a confusing variety of contact-related features, some steeply inclined and some near horizontal. Originally these were attributed to several *en échelon* segments of a dyke that terminated close to the present land surface at a broad, gently sloping, near-planar upper surface. However, a geophysical survey has shown that the features are better explained by a series of step-and-stair transgressions that result in alternating dyke-like and sill-like sectors of the intrusion. This re-interpretation has in no way detracted from the potential international importance of the site, which preserves a wide variety of interesting features associated with such structural perturbations in an otherwise regionally persistent major dyke.

Of particular interest are near-horizontal joints and zones of large flattened and elongate amygdales that are prominent close to the upper contacts of the sill-like sectors. The original inner surfaces of the gas bubbles are revealed where the infilling material has been removed by later erosion and these show miniature 'ropey' flow structures. Such structures, which are very rare or possibly unique worldwide, have been used to determine the final flow direction of magma in the dyke.

WYDON, NORTHUMBERLAND (NY 695 629)

S.C. Loughlin

Introduction

The Wydon GCR site, on the north bank of the River South Tyne, 1.5 km south-west of Haltwhistle station, is an excellent natural exposure of the Haltwhistle Dyke, a tholeiitic basalt associated with the Whin Sill-complex (Figure 6.37). The dyke is orientated ENE–WSW and is part of the St Oswald's Chapel Subswarm that extends discontinuously between Haltwhistle and Druridge Bay and has also been proved beneath the North Sea (Randall, 1995b). Natural inland exposures of dykes associated with the Whin Sill-complex are rare and, although many dykes have been quarried, most of the quarries have been infilled or have become overgrown. In coalfield areas, natural exposures and quarries have been lost through opencast working of coal from the surrounding strata. This rare exposure is therefore of considerable national significance.

The general geology of the site is also of interest. The dyke is intruded into flat-lying Namurian sandstones with thin intercalations of mudstone, and is overlain by Quaternary till containing a wide variety of igneous and sedimentary clasts.

The general geology of the nearby Roman Wall district has been described by Wallis (1769), Winch (1817), Tate (1868) and Johnson (1959). The Geological Survey mapped central and southern Northumberland in the 1870s and six-inch sheets 106NE and 106SE were published in 1881. A revision survey was completed in 1975 and 1:50 000 Sheet 13 (Bellingham), with an accompanying memoir, was published in 1980 (Frost and Holliday, 1980). It was Holmes and Harwood (1928) who first suggested that the dykes were comagmatic with the Whin Sill-

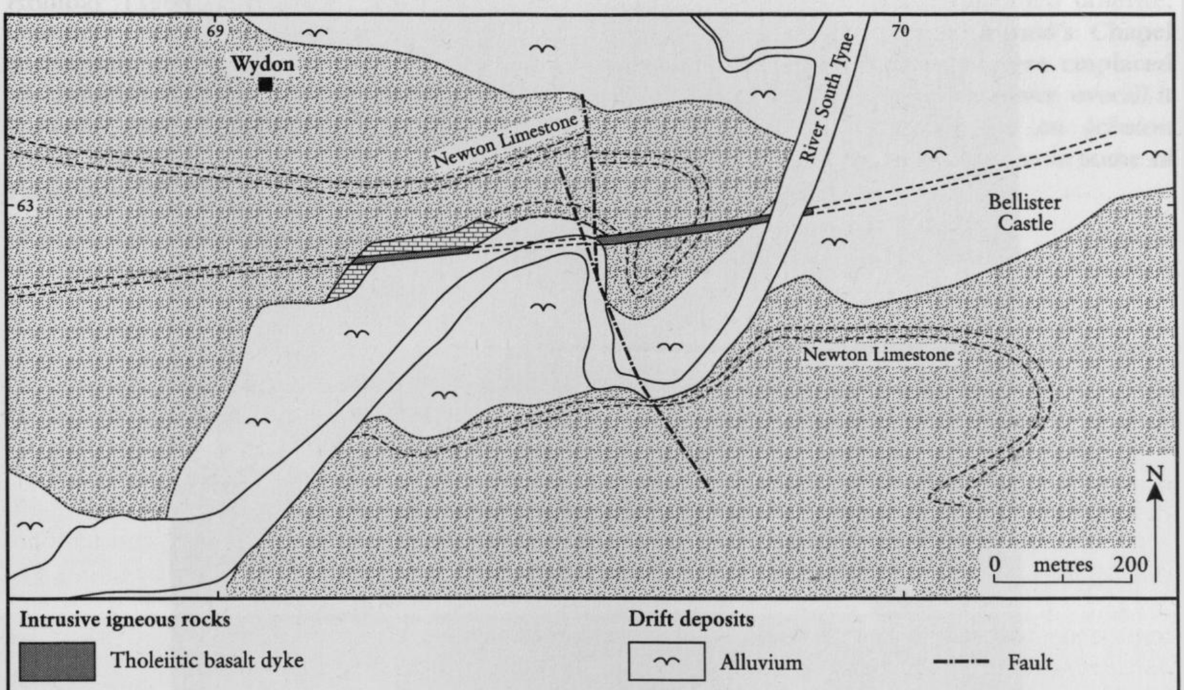

Figure 6.37 Map of the area around the Wydon GCR site. Based on Geological Survey 1:10 560 Sheet Northumberland, New Series 89SW (1926).

complex, and Thorpe and Macdonald (1985) included analyses of the dykes in their geochemical study of the complex. Popular field guides of the area include those by Scrutton (1995) and Johnson (1997).

Description

The sense of the *en échelon* offsets in the St Oswald's Chapel Subswarm is sinistral, like that of the High Green Subswarm to the north, but the offsets are not as well developed. Near Haltwhistle the subswarm trends ENE, almost parallel to the Roman Wall outcrops of the Great Whin Sill, and following closely the line of the River South Tyne. Near Hexham, it swings to a more north-easterly trend, converging on the High Green Subswarm. Dykes regarded as part of the St Oswald's Chapel Subswarm also include the Erring Burn Dyke, the Bavington Dyke and the Causey Park Dyke, which has been traced for some distance offshore (Randall, 1995b).

At the Wydon GCR site the dyke forms a significant feature, over 10 m in height and *c.* 6 m in width (Figure 6.38). Contacts with the surrounding sedimentary rocks are obscured by slumped and fallen rock debris but flat-lying sedimentary rocks crop out in low cliffs along

Figure 6.38 The Haltwhistle Dyke, cutting sandstones and overlain by till, on the bank of the River South Tyne near Wydon. (Photo: British Geological Survey, No. A4129, reproduced with the permission of the Director, British Geological Survey, © NERC.)

the river to the east and in parts of the scarp to the west. These rocks comprise sandstones with thin intercalated layers of carbonaceous mudstone. The basalt of the dyke is uniformly fine grained and it is petrologically and geochemically very similar to rocks of the Whin Sill-complex (Frost and Holliday, 1980; Thorpe and Macdonald, 1985). Plagioclase feldspar is normally zoned, accessory olivine is replaced mainly by talc, augite is partially altered to smectite and there are abundant fresh opaque oxides. The segment of this subswarm farther to the east, known as the Erring Burn Dyke, is petrologically slightly different, containing ragged hypersthene crystals and rare large xenocrysts of labradorite.

Interpretation

The rocks of the Whin Sill-complex and dyke-swarm produce notable magnetic anomalies. Whereas anomalies over the sills are relatively low, those associated with the dykes are pronounced, enabling them to be traced where there is no surface exposure and enabling their sub-surface form to be ascertained. Frost and Holliday (1980) traced the dykes of the St Oswald's Chapel Subswarm across the Bellingham district and found that several of the *en échelon* segments coincide with faults. However, overall the subswarm follows an ENE trend, which is similar to the fabric of the Lower Palaeozoic basement.

Holmes and Harwood (1928) suggested that the two most northerly subswarms (the Holy Island and High Green subswarms) were emplaced along *en échelon* fractures during a period of east–west compression, and further work by Shiells (1961) and Wilson (1970) tended to support this. However, Anderson (1951) preferred to consider the dykes as sub-parallel and emplaced during regional tension. The more southerly St Oswald's Chapel and Hett subswarms were considered to have been affected by the edges of the Alston Block (Randall, 1995b) because they are more linear and the *en échelon* structure is not as well developed.

Conclusions

The Wydon GCR site provides one of the best natural exposures of a Late Carboniferous tholeiitic dyke in northern England. The dyke is only 6 m wide but it forms a positive topographical feature that runs for a considerable distance along the banks of the River South Tyne. The dyke cooled rapidly because it is thin and it is therefore a uniformly fine-grained basalt, rather than a medium-grained dolerite. The dyke is part of the St Oswald's Chapel Subswarm, segments of which were emplaced along pre-existing fractures. However, overall it follows a curving path and the *en échelon* structure is not as well developed as in some of the other subswarms.