Chapter 6 Tholeiitic sills and dykes of Scotland and northern England

Introduction

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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 (Figure 6.1) and (Figure 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).

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 geo-chemical 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 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 inter-growth 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 'tholeiitie. 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 (chloro-phaeite 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 Queens-ferry 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 use and many are, or have been, popular rock-climbing venues (e.g. Ratho, Ravefrig, 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 Du ckmantian (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 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 Fame 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 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 Mel 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 at,* 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 '*échelon*' 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 sub-swarm, 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.

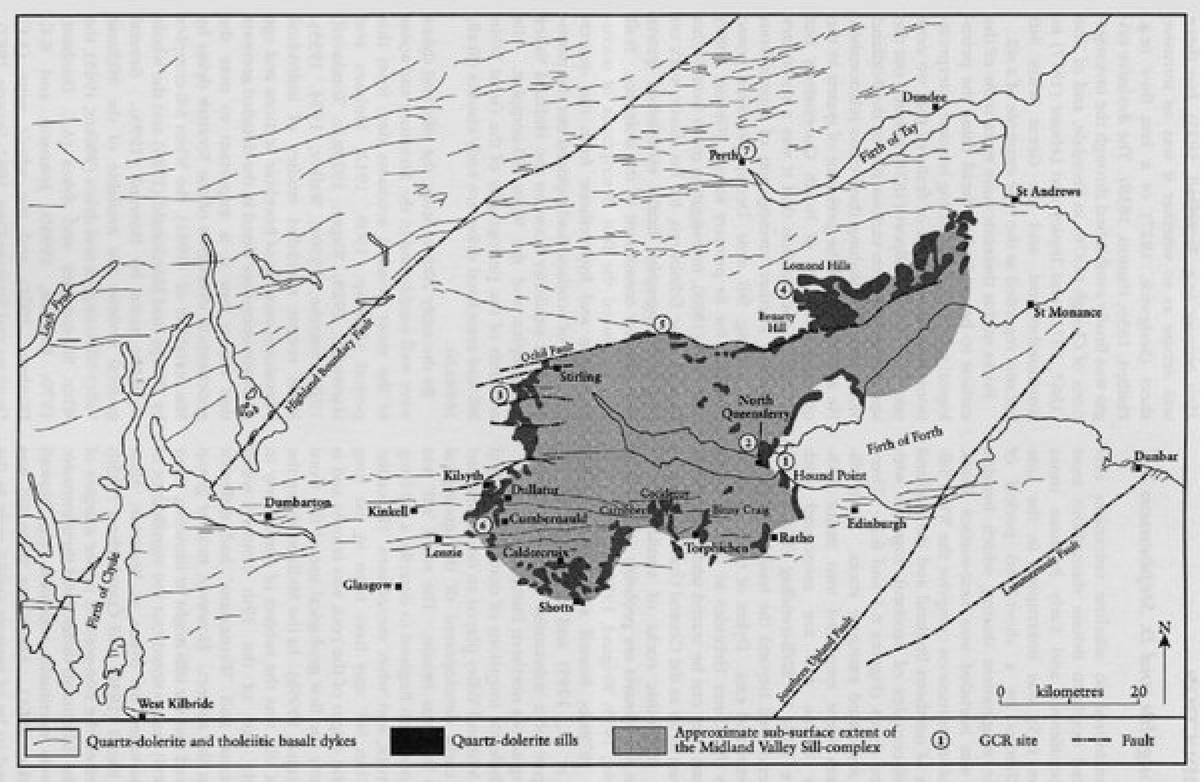
Relatively pure limestones, such as the Melmerby Scar Limestone in Upper Teesdale, exhibit extensive recrystallization to give a saccharoidal texture and readily disaggregate on weathering. This 'sugar limestone' gives rise to a distinctive suite of soils that supports the renowned alpine flora on Cronkley and Widdybank fells. Impure limestones are converted into calc-silicate rocks containing a wide variety of minerals including garnet, idocrase, wolla-stonite, 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 wolla-stonite 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-homfels 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.

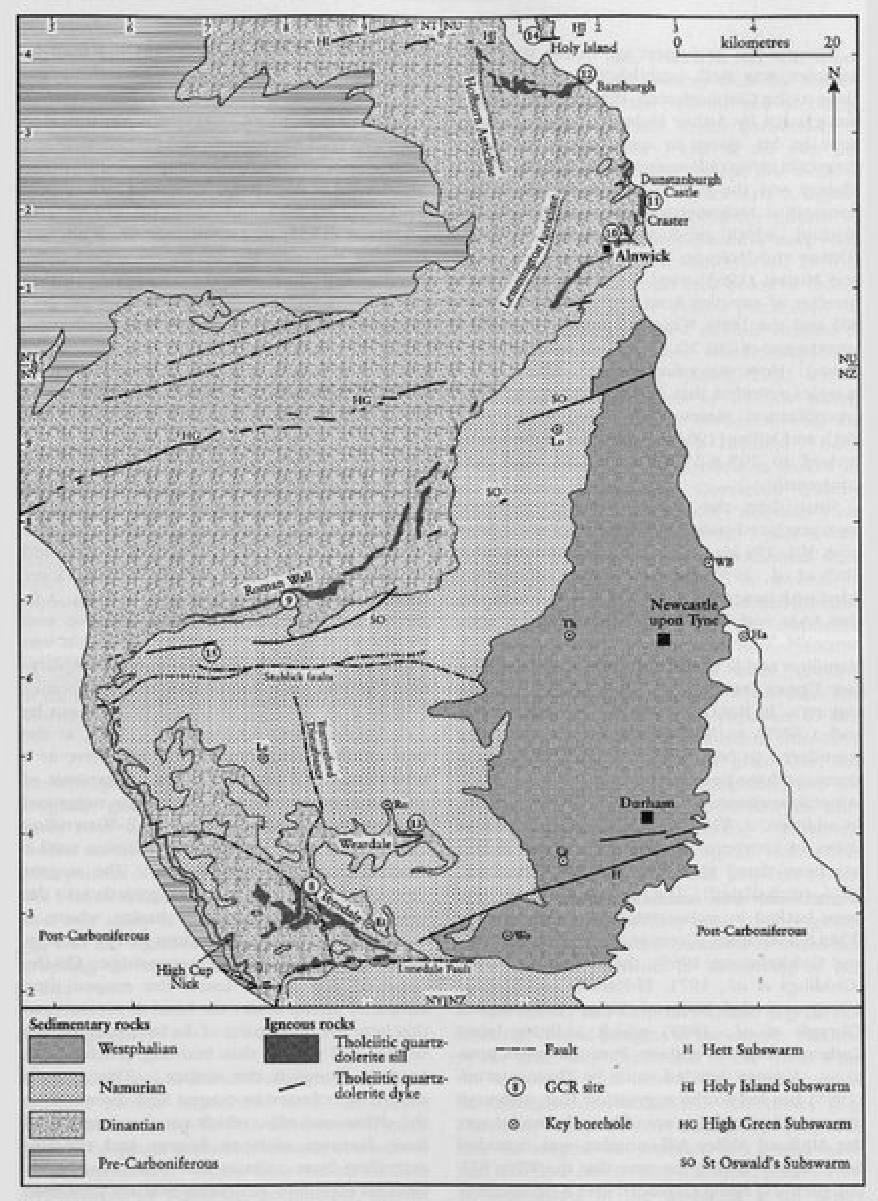
In the Alston Block, the Whin sills and dykes are cut by mineral veins of the Northern Pennine Orefield (see Upper Teesdale GCR site report). The dolerite acts as a brittle wall-rock, like the limestones and the more massive sandstones, and hence is a favourable host for mineralization. In the Blackdene 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).

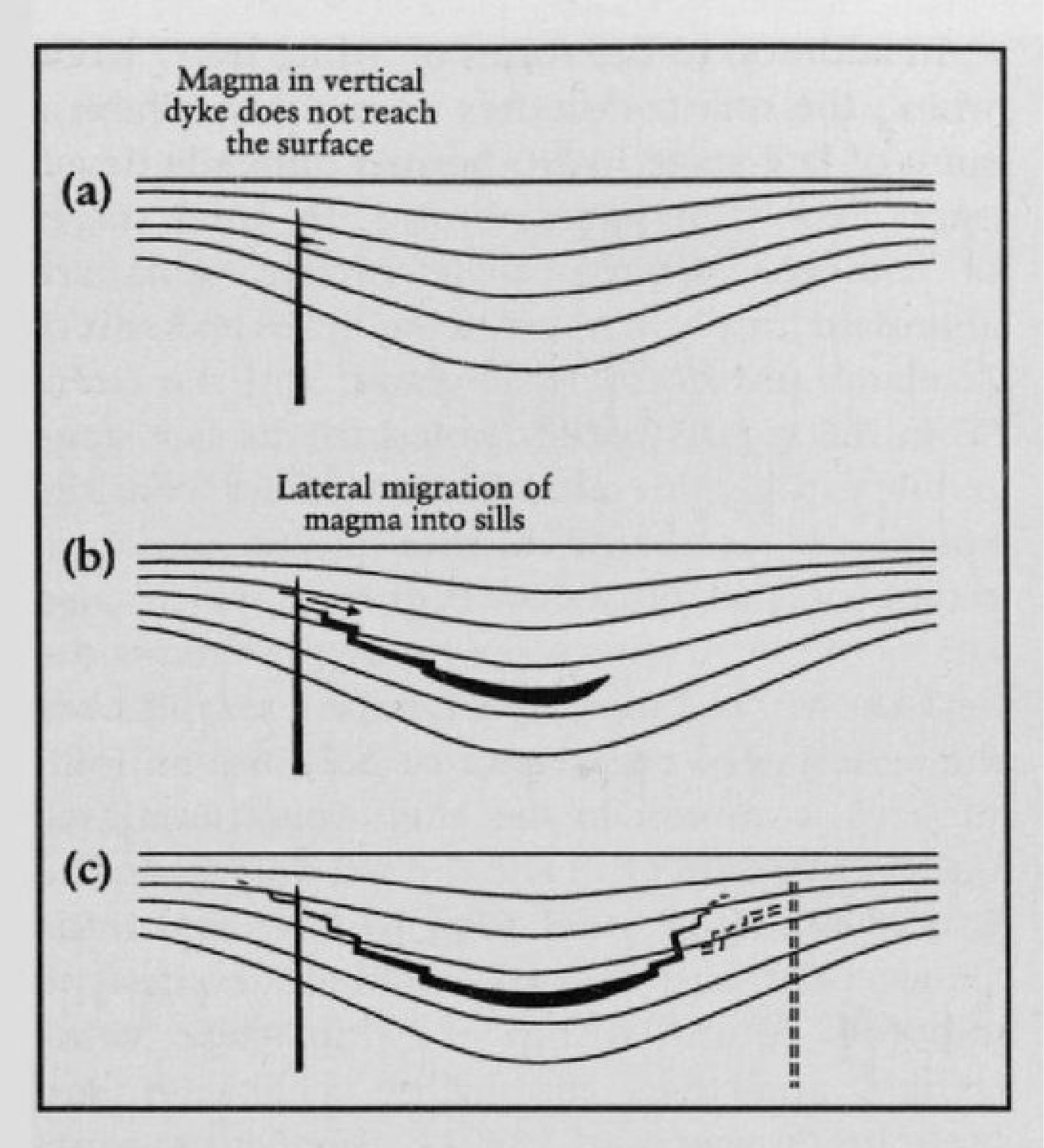
References



(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).



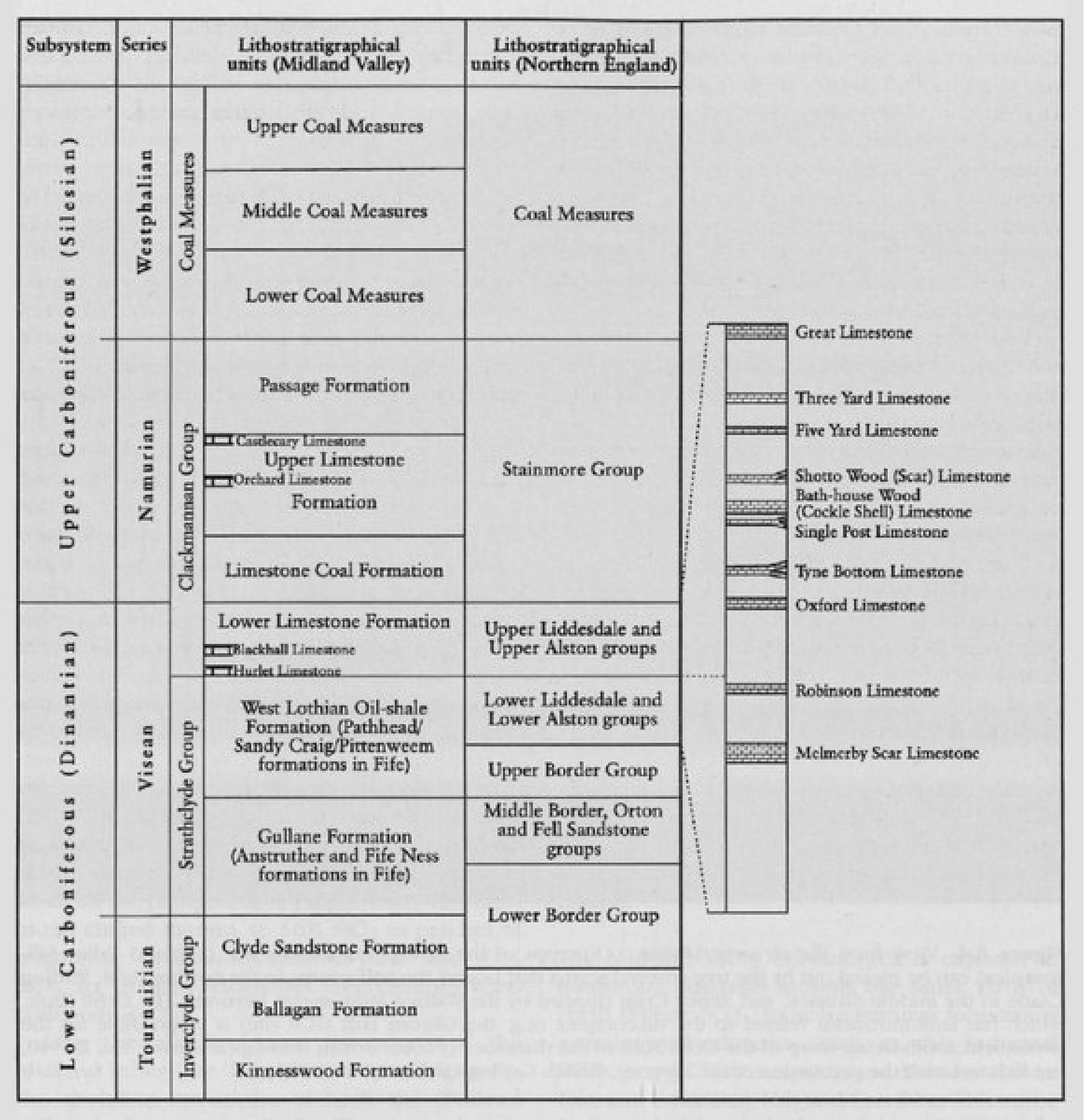
(Figure 6.2) Map of north-east England, showing the area intruded by the Late Carboniferous tholeiitic Whin Sill-complex and associated dyke subswarms. GCR sites: 8 = Upper Teesdale; 9 = Steel Rigg to Sewingshields Crags; 10 = Longhoughton Quarry; 11 = Cullernose Point to Castle Point; 12 = Budle Point 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).



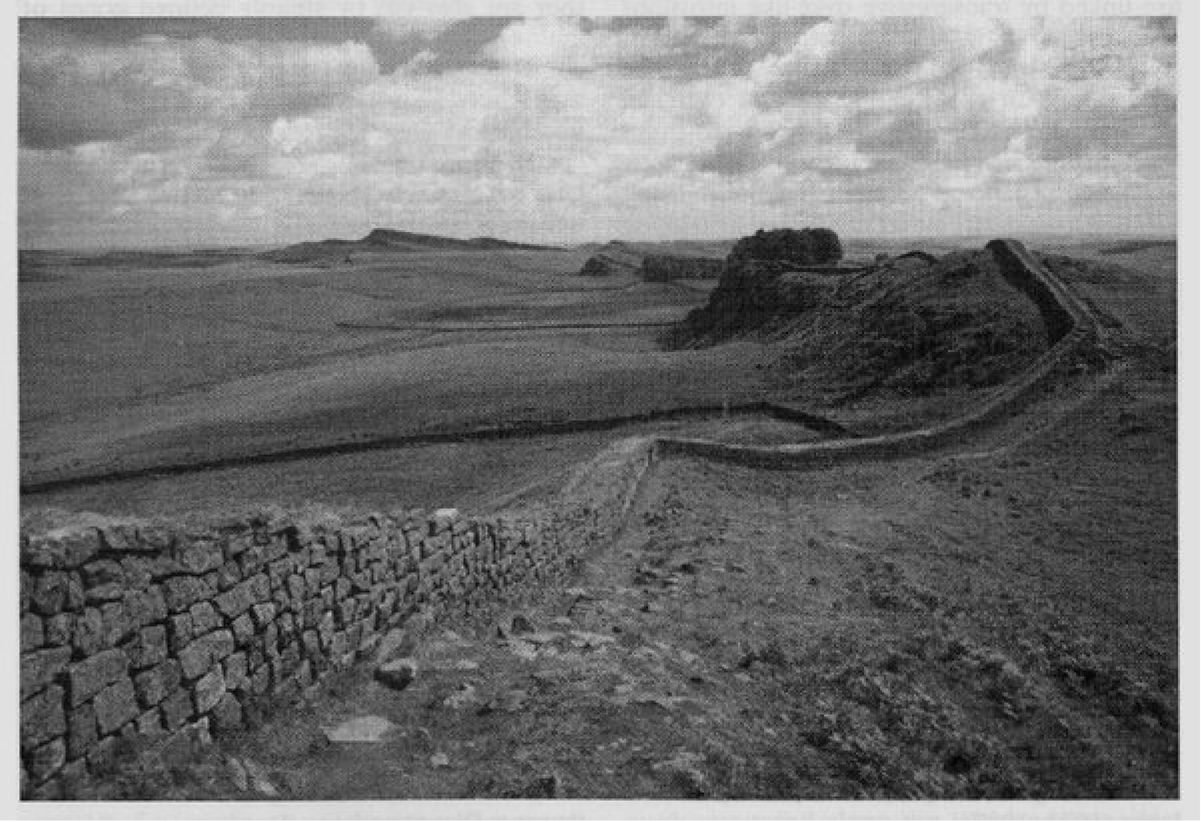
(Figure 6.3) Diagram to illustrate the mechanism of intrusion of the Midland Valley Sill-complex and the Whin Sill-complex, suggested by Francis (1982). (a) dykes are intruded to 0.5–1.0 km below the surface; (b) lateral intrusion of magma leads to gravitational flow down-dip and accumulation of magma 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.

(Figure 5.8) Basic sill intruding and transgressing sedimentary rocks of the West Lothian Oil-shale Formation and altered to 'white trap', South Queensferry shore. The hammer shaft is about 35 cm long. (Photo: A.D. McAdam.)

(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.)*

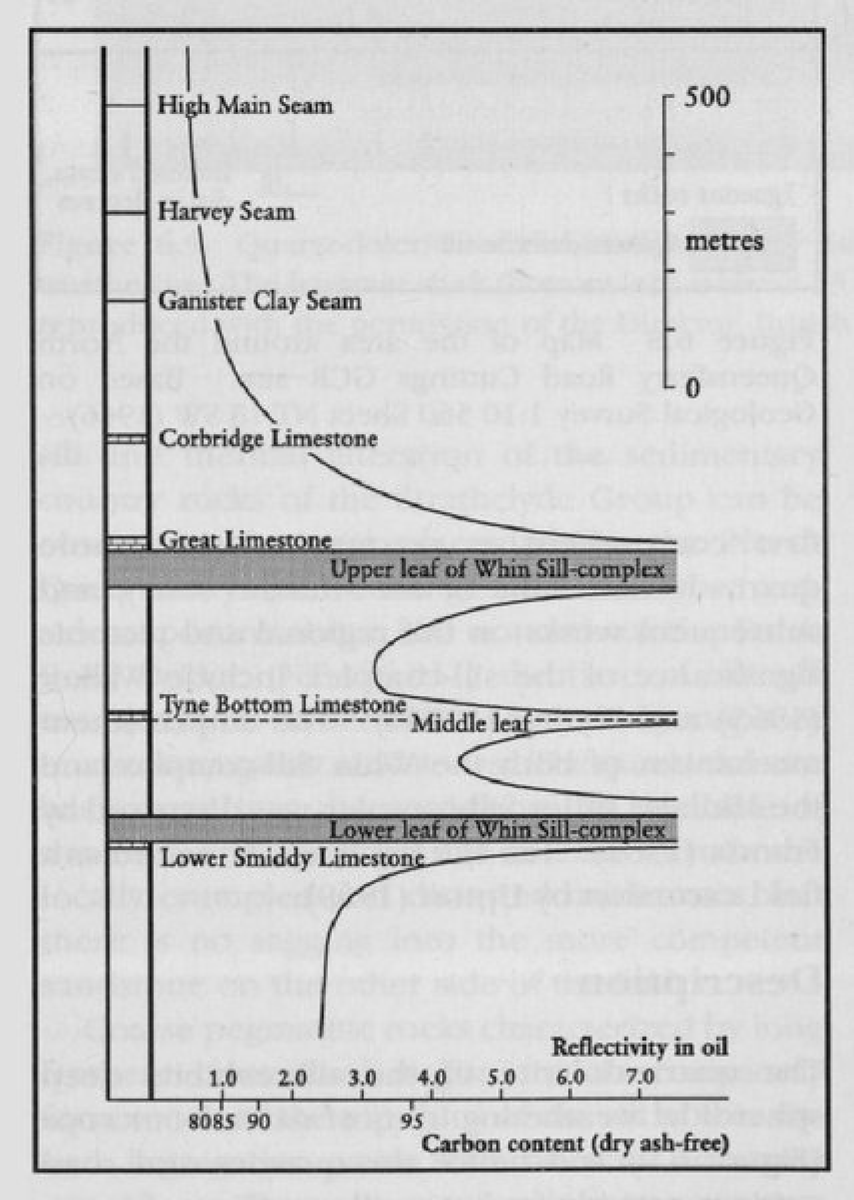


(Figure 6.5) Simplified stratigraphical column showing the lithostratigraphy of Carboniferous rocks cut by the Stephanian tholeiitic sills and dykes of Scotland and northern England. In northern England, the Liddesdale Group is found in the Northumberland Basin whilst the Alston Group occurs on the Alston 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).



(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.)

(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.)



(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).