Carboniferous and Permian Igneous Rocks of Great Britain

North of the Variscan Front

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GCR Editor: D. Palmer

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Chapter 7

Carboniferous and Permian igneous rocks of central England and the Welsh Borderland

INTRODUCTION

C.N. Waters

Carboniferous intrusive and extrusive rocks crop out in a number of relatively small and isolated centres in the Derbyshire Peak District, the Black Country of the West Midlands, the Welsh Borderlands and the Bristol area (Figure 7.1). Boreholes for oil and coal exploration in the East Midlands, Oxfordshire and Berkshire have proved additional Carboniferous igneous rocks at depth, showing a more extensive distribution than the surface exposures. Igneous rocks of Carboniferous and Permian age, south of the Variscan Front, are described fully in the *Igneous Rocks of South-West England* GCR Volume (Floyd *et al.*, 1993). These include Dinantian and Early Permian alkaline lavas and pyroclastic rocks, and the calc-alkaline granite batholith that was intruded during Late Carboniferous to Early Permian times.

The igneous rocks of central England were of importance in the early development of the understanding of geological processes when Hutton (1788) recognized that the 'ragstones' of south Staffordshire and 'toadstones' of Derbyshire are comparable to lavas erupted from active volcanoes and that these areas had formerly seen volcanic activity. Subsequent research has provided information on field relations and petrography, and more recently work on the geochemistry has contributed to the development of understanding of the tectonic evolution of the UK during the Carboniferous Period.

Carboniferous igneous activity in this area is all considered to have occurred in a within-plate environment on the Laurussian continent (see Chapter 1). There is no evidence of direct input from the subduction-related magmatism prevalent in south-west England at the time (Upton, 1982; Macdonald *et al.*, 1984). The nature of the igneous activity in this region evolved in response to changes in tectonic processes and can be broadly sub-divided into events of Dinantian and Silesian age (Figure 7.2). The products of all these events show a typical lack of differentiation in comparison with their Scottish equivalents, probably because only small volumes of magma were produced and the eruptive activity was short-lived (Francis, 1970a).

Dinantian igneous activity

The main control on development of Dinantian volcanicity throughout England and Wales was north–south lithospheric stretching and thinning associated with the formation of blocks and basins (Leeder, 1982). Much of the activity occurred along lines of pre-existing basement lineaments which commonly bound the main blocks and basins (Francis, 1970a). The main centre of igneous activity at this time was in the Derbyshire Dome, with minor volcanism in the Bristol and Wenlock areas and in the East Midlands.

In Derbyshire, basaltic lavas, pyroclastic rocks and sills occur within a Dinantian carbonate succession. The extrusive rocks are associated with Visean sedimentary rocks, which can be determined biostratigraphically to be late Holkerian to late Brigantian in age, although the majority of activity occurred during early Brigantian times (Walters and Ineson, 1981). The sills appear to be genetically related to the extrusive rocks and are probably also of late Dinantian age, although whole-rock K-Ar and Ar-Ar dates on the sills suggest they are considerably younger than the lavas (Fitch *et al.*, 1970; M. Timmerman, pers. comm., 2002); the discrepancy may be a function of hydrothermal alteration.

In general, the igneous bodies are poorly exposed, with active or former quarrying operations providing most of the important exposures. Arnold-Bemrose (1894, 1907) identified two major centres of igneous activity at Matlock and Miller's Dale, covering areas of about 200 km^2 and 145 km^2 respectively (Francis, 1970a). The GCR sites of **Litton Mill**, **Water Swallows Quarry**, **Tideswell Dale** and **Calton Hill** are all located in the more northerly Miller's Dale Centre (Figure 7.3). Francis (1970a) identified at least 14 agglomerate vents, and Walters and Ineson (1981) recognized 30 distinct lavas and beds of pyroclastic rock. Stevenson and Gaunt (1971) noted a lack of any relationship between the flows and the vents and suggested an origin through fissure eruptions. However, Walters and Ineson (1981) suggested that the volcanic rocks were the product of small, short-lived central vent volcanoes and proposed some correlations based on the more laterally extensive pyroclastic rocks. Aitkenhead *et al.* (1985) identified two further local eruptive centres, largely from subsurface occurrences, and renamed the Matlock and Miller's Dale centres 'Bonsall' and 'Tunstead' respectively. They noted that the eruptions from the four centres were not contemporaneous and that lavas cannot be correlated from one centre to another. Wilkinson (in Neves and Downie, 1967) has proposed that intrusions and volcanic vents

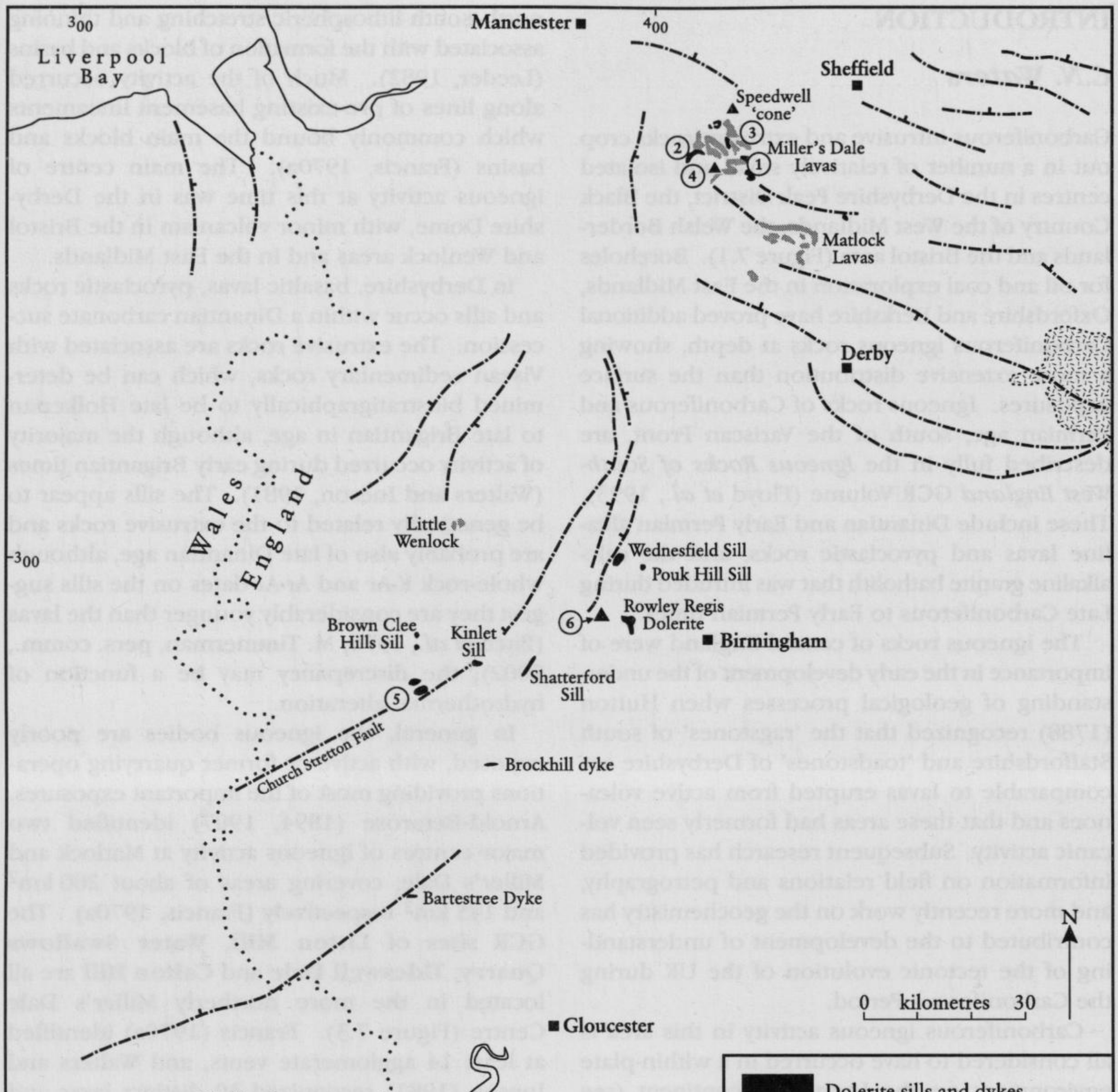

Figure 7.1 Map of central England and the Welsh Borderlands showing locations of Carboniferous igneous rocks and the GCR sites. GCR sites: 1 = Litton Mill Railway Cutting; 2 = Water Swallows Quarry; 3 = Tideswell Dale; 4 = Calton Hill; 5 = Clee Hill Quarries 6 = Barrow Hill; 7 = Middle Hope; 8 = Spring Cove; 9 = Golden Hill Quarry. Based on Geological Survey 1:625 000 Geological map of the UK South (1979).

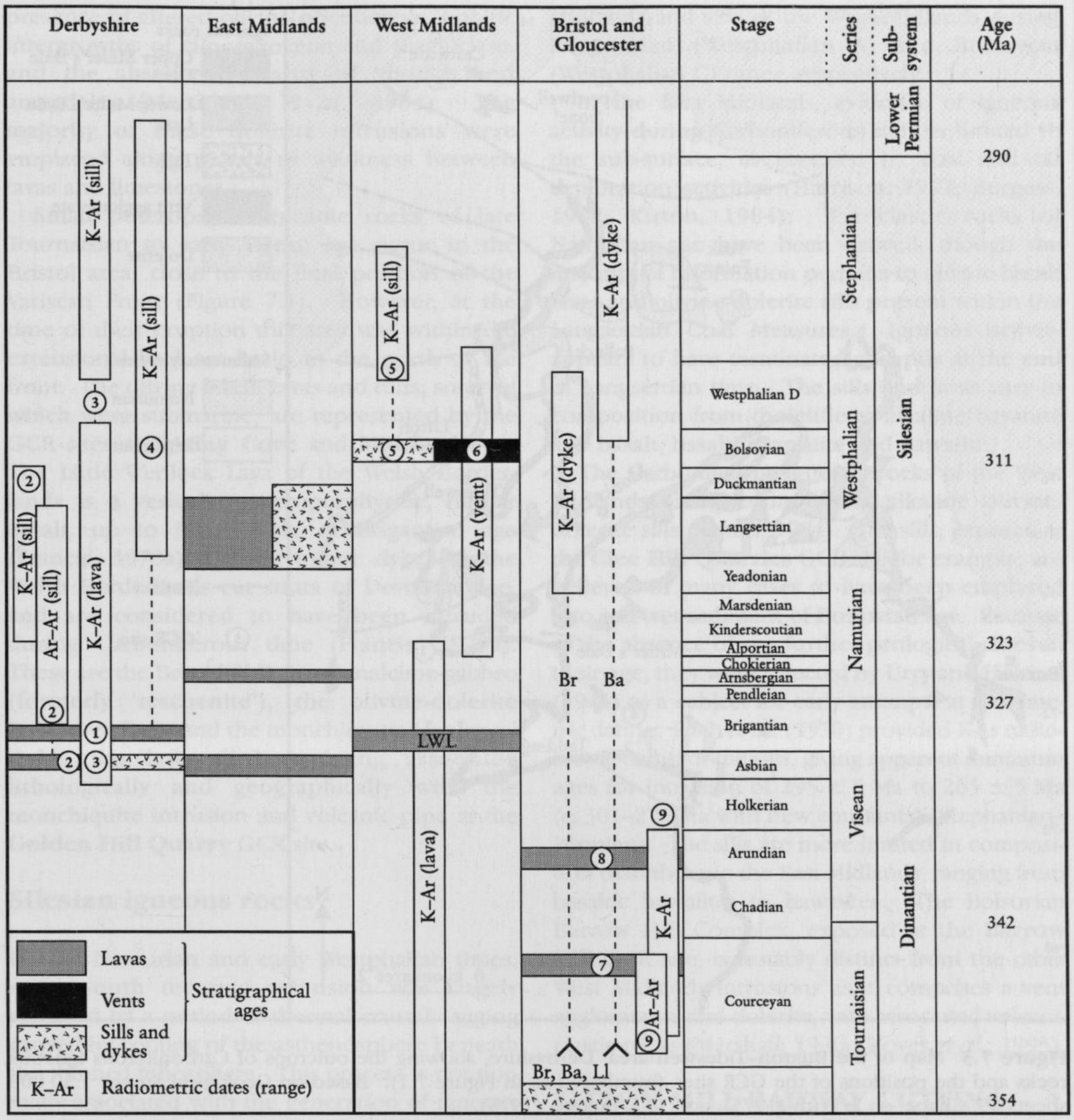

Figure 7.2 Approximate ages and stratigraphical distribution of selected igneous rocks from central England and the Welsh Borderlands. The GCR sites are numbered as for Figure 7.1. (Ba = Bartestree Dyke; Br = Brockhill Dyke; Ll = Llanllywel Monchiquite Dyke; LWL = Little Wenlock Lavas.) After Francis (1970a); and Kirton (1984). The timescale is that of Gradstein and Ogg (1996).

tend to coincide with WNW-trending anticlinal axes or occur along the margins of structural blocks.

The lavas are typically only a few tens of metres in thickness, but with some discrete flows up to 42 m thick (Francis, 1970a) and composite or compound flows in places (Walters and Ineson, 1981; Ineson and Walters, 1983; Macdonald *et al.*, 1984). The two main lava units exposed at GCR sites in Derbyshire are the Upper Miller's Dale Lava and the Lower Miller's Dale Lava (note that the lithostratigraphical name refers to them in the singular despite the common presence of multiple lava flows). They are usually highly altered, fine-grained, olivine-phyric and aphyric basalts. The lavas are commonly vesicular with amygdales of carbonate, chlorite, chalcedony or albite (Macdonald *et al.*, 1984). Many of the lavas

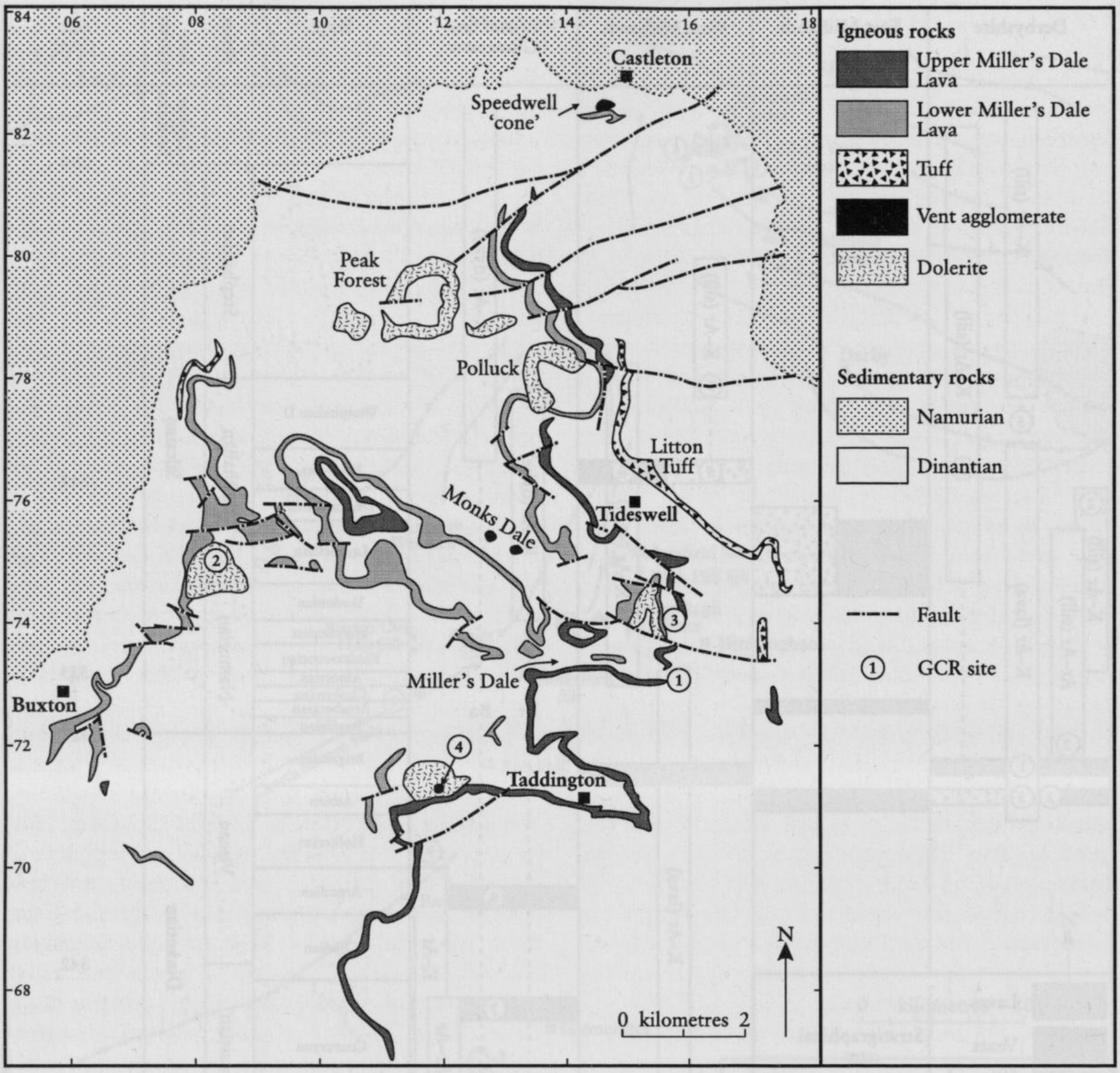

Figure 7.3 Map of the Buxton–Tideswell area, Derbyshire, showing the outcrops of Carboniferous igneous rocks and the positions of the GCR sites (numbered as in Figure 7.1). Based on Geological Survey 1:50 000 sheets 99, Chapel en le Frith (1975); and 111, Buxton (1978).

are thought to have been subaerial eruptions upon an emergent platform, and interdigitated breccias are characteristic of subaerial autobrecciation, formed in response to friction or internal disruption of flows (Ineson and Walters, 1983). However, it has been suggested that some lavas flowed across wet sediments, terminating locally in shallow water (Cheshire and Bell, 1977; Walkden, 1977; Macdonald *et al.*, 1984), and pillow lavas are recorded in marine basinal facies marginal to the platform. Tuffs are typically subordinate to the lavas, commonly preceding and/or following lava eruption (Ineson and Walters, 1983). However, K-bentonites are widespread, most notably in the Bee Low Limestones of Asbian age, which contain 30–40 beds, generally less than 3 cm thick, though locally up to 1.25 m thick (Walkden, 1972, 1977; Aitkenhead *et al.*, 1985). Tuff-cones have been inferred or recognized at numerous localities and typically contain vitric and devitrified lapilli-tuffs, interpreted as the products of phreatomagmatic activity due to the interaction of magma and groundwater in the vent (Ineson and Walters, 1983).

The sills are dominantly medium- to coarse-grained olivine-dolerites, distinguished by the presence of altered olivine phenocrysts, ophitic intergrowths of clinopyroxene and plagioclase, and the absence or rarity of vesicles and amygdales (Macdonald *et al.*, 1984). The majority of these dolerite intrusions were emplaced along planes of weakness between lavas and limestones.

Small outcrops of volcanic rocks of late Tournaisian to early Visean age occur in the Bristol area, close to the final position of the Variscan Front (Figure 7.1). However, at the time of their eruption this area was within the extensional back-arc basin to the north of the front. The olivine basalt lavas and tuffs, some of which were submarine, are represented by the GCR sites at **Spring Cove** and **Middle Hope**. The Little Wenlock Lava of the Welsh Borderlands is a vesicular, microporphyritic, olivine basalt, up to 30 m thick, of Brigantian age (Francis, 1970a). Three minor dykes in the Welsh Borderlands cut strata of Devonian age, and are considered to have been intruded during Carboniferous time (Francis, 1970a). These are the Brockhill Dyke of analcime-gabbro (formerly 'teschenite'), the olivine-dolerite Bartestree Dyke and the monchiquitic Llanllywel Dyke, the last of these being associated lithologically and geographically with the monchiquite intrusion and volcanic pipe at the **Golden Hill Quarry** GCR site.

Silesian igneous rocks

During Namurian and early Westphalian times, north–south tectonic extension was largely replaced by a period of thermal crustal sagging caused by cooling of the asthenosphere beneath the thinned lithosphere. This process is not normally associated with the generation of igneous activity (Leeder, 1982). However, volcanic activity continued, although less abundantly and with relatively few lavas. Volcanicity became more explosive with production of tuffs and thin ash-fall clays, referred to as bentonites or tonsteins, typically a few millimetres to centimetres thick (Trewin, 1968; Francis, 1969; Price and Duff, 1969; Spears, 1970). Acidic ash-fall deposits generally cover very large areas and have been associated with Variscan volcanic activity at a destructive plate margin present to the south of Britain (Spears and Kanaris-Sotiriou, 1979). Basic bentonites are more locally developed and may relate to the alkaline igneous activity that produced the dolerite sills and lavas of the East Midlands and sills of the West Midlands during Langsettian (Westphalian A) and Bolsovian (Westphalian C) times, respectively.

In the East Midlands, evidence of igneous activity during Carboniferous time is limited to the sub-surface, as revealed by coal and oil exploration activities (Harrison, 1977; Burgess, 1982; Kirton, 1984). Pyroclastic rocks of Namurian age have been proved, though the majority of information pertains to olivine basalt lavas and olivine-dolerite sills present within the Langsettian Coal Measures. Igneous activity appears to have terminated abruptly at the end of Langsettian time. The sills and lavas vary in composition from tholeiitic to alkaline basanite and basalt, basaltic hawaiite and hawaiite.

The Carboniferous igneous rocks of the West Midlands are predominantly alkaline olivine-dolerite sills (Kirton, 1984). The sills, exposed at the **Clee Hill Quarries** GCR site for example, are believed in many cases to have been emplaced into still-wet sediment of Bolsovian age. Because of the absence of any further geological clues to their age, they were selected by Urry and Holmes (1941) as a subject for early attempts at radiometric dating. Fitch *et al.* (1970) provided K-Ar radiometric dates for the sills, giving apparent minimum ages for intrusion of 295 ± 5 Ma to 265 ± 5 Ma (*c.* 301–271 Ma with new constants) (Stephanian–Permian). The sills are more limited in composition than those in the East Midlands, ranging from basaltic hawaiites to hawaiites. The Bolsovian Barrow Hill Complex, exposed at the **Barrow Hill** GCR site, is notably distinct from the other West Midlands intrusions as it comprises a vent agglomerate and dolerite, with associated volcaniclastic rocks (Marshall, 1946; Glover *et al.*, 1993).

LITTON MILL RAILWAY CUTTING, DERBYSHIRE (SK 158 729)

C.N. Waters

Introduction

The Litton Mill Railway Cutting, in the Wye Valley of Derbyshire, represents the Brigantian Upper Miller's Dale Lava. Here, the lava occurs within a limestone sequence and appears to have flowed across an eroded surface into a lagoonal embayment. The flow-front is well exposed and is shattered and brecciated as a consequence of contact with water. Numerous publications have referred to this section and the significance of the dramatic thinning and termination of the Upper Miller's Dale Lava (Green *et al.*, 1887; Arnold-Bemrose, 1907; Cope, 1933, 1937; Walkden, 1977).

The Upper Miller's Dale Lava, which is also present at the **Calton Hill** GCR site, commonly consists of several lava flows. The lavas are of Brigantian age and are younger than the Asbian Lower Miller's Dale Lava seen at the **Water Swallows Quarry** and **Tideswell Dale** GCR sites (Figure 7.3).

Description

The GCR site comprises a disused railway cutting, extending about 550 m to the west of the Litton Tunnel (SK 162 729) (Figure 7.4). The succession detailed below is a composite stratigraphical section (shown in descending order) from the former railway cutting and the cliffs below the cutting on the south bank of the River Wye. It is derived from descriptions by Cope (1937), R.A. Eden (unpublished Geological Survey field notes, 1954) and Walkden (1977).

	Thickness (m)
Monsal Dale Limestones: 'Priestcliffe Beds' of Cope (1937)	
Limestone, dark grey, thinly bedded, very fine-grained with chert nodules; a marked discontinuity is present in the lower part of the section (Figure 7.5)	17.95
Limestone, grey, dark grey towards top, fine grained, irregular bedded with rounded fragments of decomposed lava near base	1.37
Upper Miller's Dale Lava	
Basalt, brown-weathered, upper 1.52 m poorly exposed, rough flow-banding, rounded masses of harder material up to 0.61 m diameter	up to 5.18
Monsal Dale Limestones: including 'Station Quarry Beds' of Cope (1937)	
Limestone, dark grey, thinly bedded, fine grained, locally crinoidal, cherty in places especially in the upper part, 10 cm-thick K-bentonite 4 m above base; irregular base (unconformity) with pot-holes in underlying Bee Low Limestone filled with impersistent K-bentonite, up to 50 cm thick, overlying conglomerate with pale- and dark-grey limestone clasts	up to *c.* 10.00
Bee Low Limestones: Miller's Dale Beds of Cope (1937)	
Limestone, pale grey, thickly bedded, very fine-grained, but with some slightly crinoidal or shelly beds	*c.* 15.00

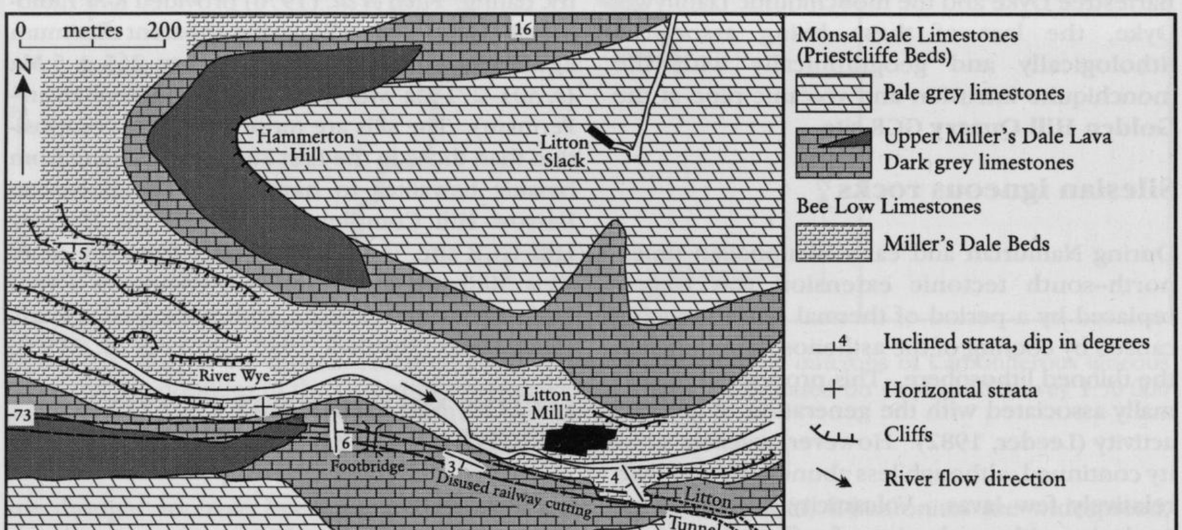

Figure 7.4 Map of the area around the Litton Mill Railway Cutting GCR site and horizontal section. After Walkden (1977).

The Upper Miller's Dale Lava is present only in the western part of the section (SK 157 730) (Figure 7.4). Here, the lava shows a rough flow-banding which dips at 40° to the east. The irregular upper surface of the lava is obscured by a small retaining wall (Figure 7.5), but was formerly seen by Cope (1933, fig. 5) with a dip toward the east of about 25°. A thin, irregular laminated tuff occurs locally beneath the lava (Cope, 1937).

At the eastern end of the cutting, at the western portal of Litton Tunnel (SK 1617 7289), the top of the Bee Low Limestones is described by Walkden (1977) as having a karstic hollow filled with limestone breccia, overlain by an impersistent K-bentonite up to 50 cm thick. A further K-bentonite band, 10 cm thick, occurs 4 m above the top of the Bee Low Limestones. This bentonite displays a relict vitroclastic texture, with rock fragments and glass shards up to 0.5 mm in diameter and bioclastic debris in a calcite matrix (Walkden, 1977).

Interpretation

The Upper Miller's Dale Lava has a typical thickness of about 30 m in Miller's Dale, but decreases markedly in thickness toward the Litton Mill Railway Cutting in the east. This GCR site provides a rare example in England of such a lateral termination of a lava flow, which is both well exposed and easily accessible.

Green *et al.* (1887) were first to recognize the lateral thinning and dying out of the lava flow. Arnold-Bemrose (1907) suggested that the absence of the flow along part of the railway cutting resulted from the presence of a fault with a downthrow of some 60 m to the east. However, in a detailed description of the cutting and adjacent area, Cope (1933, 1937) discounted the fault model and proposed that the lava died out as a flow-front about 550 m to the west of the Litton Tunnel. Walkden (1977) confirmed the presence of a flow-front and identified bentonites present laterally to the east of the

Figure 7.5 Litton Mill Railway Cutting viewed towards the south-east and showing the Upper Miller's Dale Lava (bottom right), overlain by well-bedded limestones of the Monsal Dale Limestones (above the inclined grassy ledge and re-inforcing wall). The cutting is here about 18 m deep; see hammer, bottom right. A sketch of this view, with annotation, was presented by Cope (1933, fig. 5). (Photo: British Geological Survey, No. L2270, reproduced with the permission of the Director, British Geological Survey, © NERC.)

lava. He also identified an intra-Brigantian unconformity beneath the flow and provided an interpretation of the environment of formation of the lava and of the events necessary to produce the succession seen at this site. This is summarized as follows:

1. Regional uplift at the end of Asbian time produced a karstic surface at the top of the Bee Low Limestones. Alternatively, this could have been caused by a sea-level fall (Aitkenhead *et al.*, 1985).
2. Resumed sedimentation with deposition of the Station Quarry Beds, of early Brigantian age.
3. Folding and development of a broad, low-amplitude anticline with a WNW-trending axis, referred to as the Taddington Anticline by Cope (1937), located to the south of the GCR site. The folding is associated with uplift and erosion, with localized removal of the Station Quarry Beds in the hinge of the anticline, re-exposure of the karstic surface on the top of the Bee Low Limestones and filling of pot-holes with limestone breccia, as seen at the Litton Tunnel portal (Figure 7.4). The broad syncline described by Walkden (1977) in the Bee Low Limestones beneath the railway cutting is a product of this folding event.
4. Eruption of earlier flows of the Upper Miller's Dale Lava to the west, with these flows not reaching the area of the Litton Mill Railway Cutting. Along the cutting this event is found as pyroclastic debris, evident as the lower K-bentonite present only in karstic hollows, such as at the portal of the Litton Tunnel.
5. Dormant phase associated with local subsidence and deposition of carbonates of the Monsal Dale Limestones, possibly in an embayment between inactive lava flows.
6. Resumption of extrusive activity with the earlier flows over-ridden by a lava that extends eastwards as far as the western end of the Litton Mill Railway Cutting. The tapered margin of this lava seen in the cutting is interpreted as an eastward-facing flow-front developed in a flooded embayment. The lava front displays a blocky and brecciated texture, interpreted by Walkden (1977) as a flow-foot breccia formed as a result of lava entering water and shattering. Palagonitization of the basalt is evident in places, in which devitrification of basaltic glass may have formed by rapid chill and hydration of lavas on entering water. The rapid chilling was sufficient to halt the flow of the lava and cause the development of a steep flow-front. Separate inclined sheets of lava rubble would have developed under water, giving the rough flow-banding described by Cope (1937) and Aitkenhead *et al.* (1985). The upper 10 cm-thick K-bentonite present at the Litton Tunnel portal may represent a hyaloclastitic carpet of fine-grained volcanic detritus, which accumulated in the lagoon in front of, and was over-ridden by, the advancing lava (Walkden, 1977). The irregularly bedded limestones marginal to and overlapping the lava were interpreted by Cope (1937) as having being deposited at the time of the lava flow, and the angular discordance between two steeply dipping packages of limestone beds were interpreted as a fore-set by Walkden (1977).

Evidence for two distinct extrusive events is present at Lime Works Quarry (SK 140 730) in which a *c.* 30 m-thick, non-vesicular, holocrystalline basalt is underlain by 5.2 m of tuffs with a thin amygdaloidal basalt (Walters and Ineson, 1981). The lava front observed at Litton Mill Railway Cutting is thought to equate to the thick upper flow.

Cope (1937) noted that the nearby Calton Hill Vent occurs in the core of the Taddington Anticline, with the inference that there may be a link between localized uplift and volcanic activity and that the Upper Miller's Dale Lava may have been sourced from the vent. However, the Calton Hill intrusion appears to be younger than the Upper Miller's Dale Lava and is of a different composition (see **Calton Hill** GCR site report).

Conclusions

The Litton Mill Railway Cutting GCR site shows a dominantly carbonate succession of Early Carboniferous age (*c.* 330–340 Ma), with evidence for a phase of broad folding, uplift and erosion interrupting deposition of the carbonate sediments. This folding event immediately predated the extrusion of several lavas, collectively known as the Upper Miller's Dale Lava, which crop out over a large area to the north-east of Buxton. The GCR site is representative of the upper part of this volcanic unit and is of great significance as it provides a rare opportunity in the Carboniferous rocks of England and Wales to study the lateral termination of a lava flow. This lava is interpreted as having flowed into a lagoonal embayment, becoming shattered and brecciated as it came into contact with the water. Explosive activity associated with rapid quenching of the lava may have produced a thin bed of fine volcanic detritus, which accumulated in the lagoon immediately in front of the lava flow and was subsequently partly over-ridden by the lava front.

WATER SWALLOWS QUARRY, DERBYSHIRE (SK 084 750)

C.N. Waters

Introduction

Water Swallows Quarry, now disused, about 3 km to the north-east of Buxton (Figure 7.3), has been selected as an excellent exposure of a thick olivine-dolerite sill, with spectacular examples of columnar cooling joints. The site is significant in that the Water Swallows Sill is seen to intrude the Lower Miller's Dale Lava, which is Visean in age, whereas the sill has been dated radiometrically to be around 10 Ma younger, of Namurian age (Figure 7.2). Numerous descriptions of the site have been published, notably on the geometry, petrography, geochemistry and radiometric age of the sill (Moseley, 1966; Stevenson *et al.*, 1970; Stevenson and Gaunt, 1971; Ineson *et al.*, 1983). The latest published description, by Miller (1986), provides a review of previous literature and field descriptions from exposures revealed by quarrying operations from 1971 to 1985.

The Water Swallows Sill has been intruded at the same stratigraphical level as the sill at the **Tideswell Dale** GCR site and may be genetically related.

Description

The sill has an approximately semicircular outcrop about 800 m across (Figure 7.6) and with a thickness of up to at least 80 m in the west-central part of the intrusion (Ineson *et al.*, 1983). It is the thickest sill proved in the area. The upper contact has been removed by erosion and quarrying, though Stevenson and Gaunt (1971) recorded that the top of the sill is gently discordant and is overlain by basalt of the Lower Miller's Dale Lava. Ineson *et al.* (1983)

Figure 7.6 Map of Water Swallows Quarry. Based on Geological Survey 1:10 560 sheets SK 07 SE (1968); and SK 07 NE (1959).

established that the lower contact is saucer-shaped, broadly undulating, gently discordant to the east and strongly transgressive to the west. The succession shown below (from Moseley, 1966; Stevenson *et al.*, 1970; Stevenson and Gaunt, 1971) was taken from a drainage cut in the quarry, which is no longer exposed. It shows that the sill is also underlain by basalt of the Lower Miller's Dale Lava.

	Thickness (m)
Water Swallows Sill	
Dolerite, dark grey, commonly spheroidally weathered and with prominent columnar joints, typically medium grained; local presence of smectite-filled vesicles; sharp irregular base	24.4 seen
Lower Miller's Dale Lava	
Basalt, dark grey, locally hard and white where calcitized or soft and green where chloritized; the lower part commonly decomposed yellow-brown, amygdaloidal with chlorite- and calcite-filled vesicles; pyrite veins and pyrite amygdales present near to the top with euhedral crystals up to 2 mm; sharp base	0–2.0
Bee Low Limestones	
Limestone, pale grey, with slight marmorization	0–3.0
Limestone breccia with clasts strongly altered	0–0.8
Tuff, pale green, calcareous	0–3.0

The sill comprises a coarse-grained, relatively altered, upper unit and a fine-grained, relatively unaltered, lower unit with columnar jointing. In the lower part of the quarry, where the base of the sill is approximately horizontal, columnar joints within the sill are vertical (Figure 7.7). Where the basal contact dips steeply below the deepest levels of the quarry the columnar jointing is horizontal with thin calcite veins along these joints (Moseley, 1966). The columnar joints were also described as horizontal in the north-east of the quarry, in the vicinity of a north-trending fault (Stevenson and Gaunt, 1971).

The rock of the sill is an olivine-dolerite, generally lacking the ophitic texture common in other intrusions of the area. Ineson *et al.* (1983) have shown that there is a systematic grain-size variation. The lower unit, 20–30 m thick, is fine grained and contains euhedral and partly rounded microphenocrysts of olivine, partly pseudomorphed by smectite, and labradorite feldspar. The groundmass, locally chloritized and carbonated, comprises pale-green to pale-brown anhedral augite and flow-aligned laths of labradorite. Anhedral grains of iron-titanium-manganese oxide are present and the interstitial

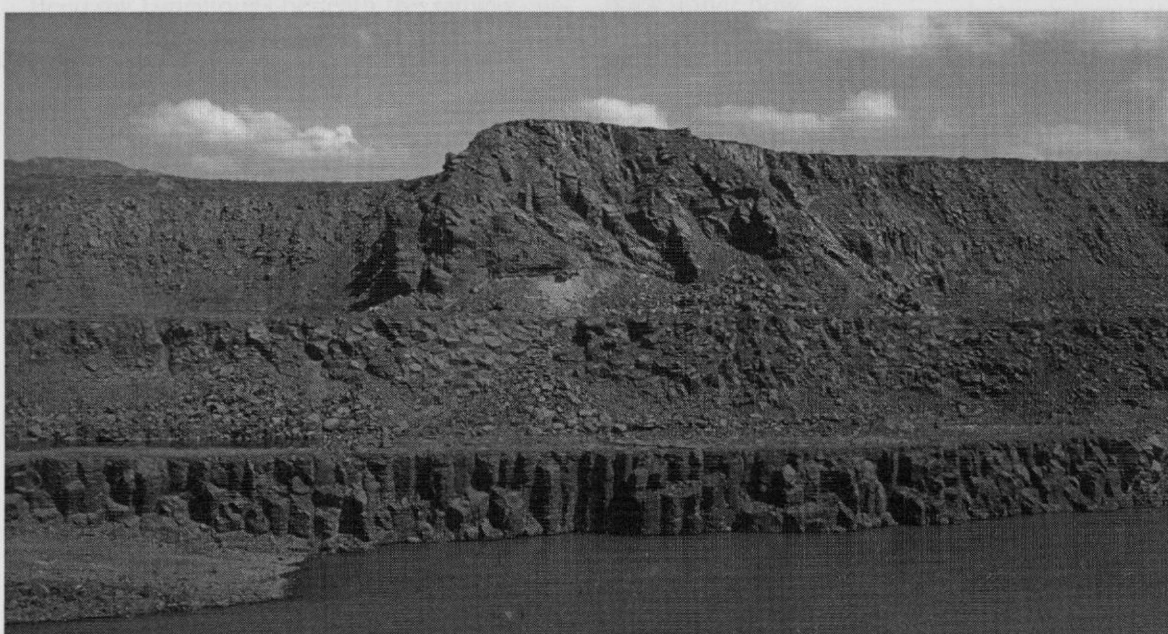

Figure 7.7 Columnar cooling joints developed in the dolerite of the Water Swallows Sill, taken in 1969. The section is probably about 20 m high, the base of the 24 m-thick sill being just below the quarry floor. Descriptions from this period indicate that the base of the sill is highly irregular and this may be the reason for the change in inclination of the joints from vertical in the lower tier, presumably above a horizontal base, to inclined away from the camera in the middle tier, where the base may be transgressing upwards. (Photo: British Geological Survey, No. L239, reproduced with the permission of the Director, British Geological Survey, © NERC.)

areas include apatite and partly devitrified glass. There is a gradation toward a middle unit, 40 m thick, slightly coarser and showing an increase in content of groundmass plagioclase and a reduction in augite content relative to the lower unit. Olivine microphenocrysts and interstitial areas have been completely replaced by smectite (Walters and Ineson, 1983). Towards the top of this unit there are spherical amygdales filled with smectite. The upper unit, of unknown thickness, is coarse grained with olivine phenocrysts, pseudomorphed by smectite, forming 25% of the rock. Miller (1986) has described the presence of rounded inclusions (5 mm to 50 cm diameter) of fine-grained basalt with some vesicles, comparable in appearance to the lower unit of the sill.

The underlying vesicular to non-vesicular lava is extensively albitized, chloritized and calcitized, and is considerably more altered than the sill. The top of the lava is irregular, commonly bulging upward into the overlying sill (Moseley, 1966).

The tuff seen at the base of the section was described by Ineson *et al.* (1983) as comprising a basal coarse tuff-breccia with rounded and iron-stained limestone clasts, on average 1 cm in diameter, overlain by lapilli-tuffs. The tuffs thicken up to 25 m beneath the north-western part of the sill, with graded beds dipping at 7°.

Mineralization is dominated by the presence of calcite amygdales and veins in the basalt; smectite and subordinate haematite, quartz and amethystine quartz veins in the sill; and pyrite in the tuffs (Miller, 1986). Moseley (1966) described the lowermost 0.6 m of the sill, containing narrow calcite veins that are parallel to its irregular basal contact. Marmorization (thermal alteration) of the limestone country rock of the sill is slight (Stevenson and Gaunt, 1971).

The olivine-dolerite sill is hypersthene-olivine-normative, with tholeiitic affinities. The lower and middle units of the sill show only minor geochemical variations, whereas the upper unit is depleted in Ca, Na, Si, Y, Zr and Sr and enhanced in Mg and total Fe (Ineson *et al.*, 1983).

Regionally, the Lower Miller's Dale Lava is underlain and overlain by beds of the Bee Low Limestones, which contain fauna indicative of late Lower *Dibunophyllum* (D_1) Zone (Stevenson and Gaunt, 1971). This shows the lavas to be Asbian in age (around 334–330 Ma on the timescale of Gradstein and Ogg, 1996). Whole-rock K-Ar age determinations of the sill gave an average date of 311 ± 6 Ma (*c.* 317 Ma with new constants) from three analyses (Stevenson *et al.*, 1970). Other, much younger dates from the same study and from a subsequent study by Ineson *et al.* (1983) were discounted as unreliable, probably due to argon loss. More recently, an Ar-Ar plateau age of *c.* 321 ± 8 Ma has been obtained from groundmass plagioclase of the sill (M. Timmerman, pers. comm., 2002), re-inforcing the suggestion of a Namurian age.

Interpretation

The presence of a sill at Water Swallows Quarry was first recognized by Arnold-Bemrose (1907) and it subsequently became well exposed through quarrying operations. Moseley (1966) provided a detailed description of the geometry of the igneous body, though he did not adequately distinguish between the sill and the underlying lavas, which he considered were both part of the same igneous event. The geological re-survey of the district established the distinct identities of the lava and sill and provided detailed petrographical and geochemical information (Stevenson and Gaunt, 1971). The discrepancy between the stratigraphical age of the Lower Miller's Dale Lava and the K-Ar radiometric age of the Water Swallows Sill led to the interpretation that the two are genetically unrelated (Stevenson *et al.*, 1970). Both the published K-Ar and the unpublished Ar-Ar radiometric dates for the sill suggest a Namurian or younger age. However, regionally the majority of dolerite sills only intrude at or below the level of the Upper Miller's Dale Lava and no intrusions are found in strata of Namurian or Westphalian age (Figure 7.3). It has been proposed that at Water Swallows Quarry the Lower Miller's Dale Lava acted as a barrier to upward migration of magma, so that the sill developed through the lateral migration of magma at or near the base of the lava (Stevenson *et al.*, 1970).

Ineson *et al.* (1983) concluded that the whole-rock K-Ar radiometric dates do not represent cooling ages, and have been reset to a younger age by argon loss, possibly during hydrothermal or deuteric alteration. They therefore proposed that the intrusions are no younger than Brigantian in age, thus re-opening the possibility that the eruption of the Lower Miller's Dale Lava and the intrusion of the sill were near-contemporaneous events.

However, the recent, unpublished Ar-Ar plateau age should not have been affected by any argon loss and would appear to confirm the time gap.

Moseley (1966) considered both the Lower Miller's Dale Lava and the sill to be lavas. He proposed that the geometry of the igneous body, in part determined from the orientation of the cooling joints, is indicative of formation within a vent, with the lava rising up a central pipe and spreading laterally as the extrusion of the Lower Miller's Dale Lava. The subsequent drilling of boreholes ascertained the saucer-shape geometry of the base of the intrusion, discounting the presence of a central pipe (Ineson *et al.*, 1983). However, Ineson *et al.* used the presence of the lapilli-tuff beneath the Lower Miller's Dale Lava, which shows a great thickening towards the north-west, to propose the presence of a tuff-cone associated with a nearby vent. This vent, as yet unlocated, was proposed to occur towards the north-west of the site. The association of the tuff-cone with the Lower Miller's Dale Lava and with the area of maximum discordance and thickness of the sill led Ineson *et al.* (1983) to suggest that this vent fed both the extrusive and intrusive igneous phases.

Arnold-Bemrose (1907) and Moseley (1966) recognized variations from fine grained to coarse grained within the sill. Ineson *et al.* (1983) determined that this grain-size variation is systematic, the lowest unit being finest and the uppermost unit being coarsest. Miller (1986) suggested that the relationship is more complex, with the coarse-grained gabbroic rocks not confined to the upper part of the sill. Geochemical variations in the sill have been attributed to the increase in proportion of olivine phenocrysts in the upper unit (Ineson *et al.*, 1983). This olivine-enriched unit cannot be a product of in-situ crystal settling as it occurs above the bulk of the intrusion. Ineson *et al.* (1983) proposed that the differentiation initially occurred in a magma chamber at depth. As the magma moved upwards, the upper olivine-poor magma was intruded first, forming the lower unit of the sill. Then, a final intrusion of the lower olivine-rich magma occurred into the top of the sill.

Although the sill lacks modal quartz, Stevenson and Gaunt (1971) indicated that it is quartz-normative, i.e. silica-saturated, and falls within the range of tholeiitic basalts. Ineson *et al.* (1983), however, suggested that these normative values do not take account of the deuteric alteration and calculated that the sill is hypersthene-olivine-normative, with tholeiitic affinities transitional to alkali basalt, and having geochemical affinities with the Lower Miller's Dale Lava.

The mineralization seen at Water Swallows Quarry has a mineral assemblage similar to that seen at the **Calton Hill** GCR site, lacking the phases more typical of hydrothermal mineralization in Derbyshire, e.g. galena, chalcopyrite and fluorite. As with **Calton Hill**, the mineralization is thought to be a late-stage, deuteric or low-temperature hydrothermal alteration (Walters and Ineson, 1983; Miller, 1986).

Conclusions

The Water Swallows Quarry GCR site is representative of the Carboniferous age dolerite sills of Derbyshire. It provides an excellent exposure of a thick dolerite sill, the Water Swallows Sill, which intrudes the Lower Miller's Dale Lava and limestones of late Visean age. Infilling of the quarry has greatly reduced the extent of section visible, though the site still provides the opportunity for future research to establish the likely relationships between the lava and the sill.

Spectacular examples of columnar joints are developed perpendicular to the sill margin in response to slow cooling of the magma. The orientation of these joints suggests that the base of the intrusion is saucer-shaped (concave-upwards). Variations in the amount of olivine at different levels in the sill have been attributed to pulses of magma from a compositionally zoned (layered) magma chamber at a deeper level.

It has been proposed that the Lower Miller's Dale Lava and the Water Swallows Sill were near contemporaneous, both having been fed from a nearby vent, which produced a tuff-cone at the surface. In contrast, radiometric dates suggest that the sill was intruded some 10 million years after the eruption of the lavas and hence that the sill and lavas are unconnected. Further study is clearly required in order to clarify the timing and the magmatic relationships, which have a wider significance for the understanding of magmatic evolution in the Carboniferous of Derbyshire.

TIDESWELL DALE, DERBYSHIRE (SK 154 740)

C.N. Waters

Introduction

The Tideswell Dale GCR site provides a good section through a dolerite sill, spatially associated with the Dinantian lavas of Derbyshire. It includes the contact with underlying limestones, which have been affected by thermal metamorphism. The Tideswell Dale Sill, as is the case with the Water Swallows Sill (see **Water Swallows Quarry** GCR site report), was intruded at the level of the Lower Miller's Dale Lava, of Asbian age (Figure 7.2), but has yielded K-Ar radiometric dates significantly younger than the stratigraphical age of the lava.

The sill is slightly discordant, transgressing from below the lavas in the east to above the lavas in the west of the dale (Wilkinson in Neves and Downie, 1967) (Figure 7.8). The Lower Miller's Dale Lava is thought in this area to occur as two distinct flows separated by a thin limestone parting (Stevenson and Gaunt, 1971). The northern and southern margins of the sill are truncated by WNW-trending faults. The site has been variously described by Arnold-Bemrose (1899, 1907), Sargent (1917), Wilkinson (in Neves and Downie, 1967), Macdonald *et al.* (1984) and Aitkenhead *et al.* (1985).

Description

The Tideswell Dale Sill was first described by Geikie (1897). Arnold-Bemrose (1899, 1907) provided the first petrographical details. He recognized a broadly symmetrical succession, about 17 m thick. The central zone, 1.8 m thick, was referred to as ophitic olivine-dolerite in which augite predominates. Above and below this zone he described 3.4 m of coarse-grained olivine-dolerite in which feldspars predominate. A fine-grained olivine-dolerite, 4.3 m thick, was described by Arnold-Bemrose (1899, 1907) as

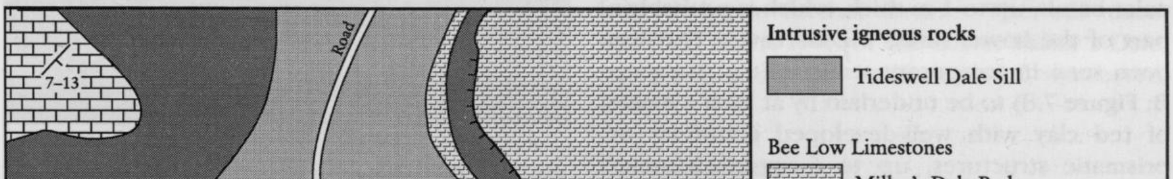

Figure 7.8 Map of the Tideswell Dale GCR site. Based on Geological Survey 1:10 560 Sheet SK 17 SE (1972).

occurring at the base and top of the intrusion. Aitkenhead *et al.* (1985) provided detailed descriptions of the petrography from the central part of the intrusion to the basal contact and were unable to identify dolerite with ophitic texture. They described the central part as medium grained, comprising phenocrysts and possible xenocrysts of olivine (12%) and augite (0.8%), set in a random intergrowth of plagioclase laths (49%), augite (20%) and opaque minerals (3.7%) with abundant interstitial devitrified glass (9%). The plagioclase is of approximate composition An_{70}. A progressive chilling is observed toward the base of the sill and at the basal contact there is extensive argillization of silicates and development of a slight flow foliation.

The Tideswell Dale GCR site comprises two former quarries located on the east side of Tideswell Dale (Figure 7.8). The main exposure (SK 155 738) (Location A; Figure 7.8) comprises about 25 m of spheroidally weathered dolerite, the upper 2.6 m containing scattered calcite amygdales. At the southern end of this quarry (SK 1547 7378), beneath the sill, there is a vesicular basalt, up to 1 m thick, which is probably a part of the Lower Miller's Dale Lava. This has been seen in temporary sections (e.g. Location B; Figure 7.8) to be underlain by at least a metre of red clay with well-developed columnar or prismatic structures, up to 6 cm in diameter (Arnold-Bemrose, 1899; Wilkinson in Neves and Downie, 1967; Aitkenhead *et al.*, 1985) (Figure 7.9). The clay has an extremely fine 'net-veined' fabric with veinlets of phyllosilicate a few microns across, in a microcrystalline matrix; the dominant mineral is an expanding-lattice mixed-layer clay (Aitkenhead *et al.*, 1985). Marmorized limestone of the Bee Low Limestones is evident below the sill on the western side of the dale (SK 1539 7410), although it is not exposed in direct contact with the sill (Wilkinson in Neves and Downie, 1967; Aitkenhead *et al.*, 1985). Arnold-Bemrose (1899) described this alteration as extending up to 3.9 m below the contact with the overlying clay and dolerite. Marmorized limestone is white, breaking with saccharoidal fracture.

Wilkinson (in Neves and Downie, 1967) described further sections in three roadside quarries at the entrance to the picnic site (SK 154 743) (Location C; Figure 7.8). These expose about 9 m of very spheroidally weathered, non-vesicular dolerite (referred to as lava by Wilkinson) with microphenocrysts of andesine and augite. This is in contact with a highly altered vesicular dolerite with pseudomorphs after olivine, flow-orientated feldspar laths and microlites of dominantly oligoclase composition. The vesicular dolerite is geochemically enriched in alkalis, especially sodium (Na_2O = 4%), in comparison with other Derbyshire lavas and sills.

Figure 7.9 Temporary exposure (July 2002) at the base of the Tideswell Dale Sill, on the east side of Tideswell Dale (Location B on Figure 7.8). The sill forms the massive natural exposures at the top of the picture and is underlain by altered basalt lava in the centre. Beneath this is a red clay with sigmoidal prismatic joints that is interpreted as a thoroughly altered lava. See text for further discussion. The cutting is 0.8 m deep. (Photo: M. Murphy.)

The geochemical analysis of the Tideswell Dale Sill provided by Macdonald *et al.* (1984) is very similar to that of the Lower Miller's Dale Lava, with relatively high SiO_2 (51.2%) and low MgO (6.24%) in comparison with other Carboniferous lavas and sills from the region. The dolerite is quartz-hypersthene-normative.

The lava was extruded onto beds of the Bee Low Limestones, which have faunal assemblages indicative of late Lower *Dibunophyllum* (D_1) Zone of Asbian age (around 334–330 Ma on the timescale of Gradstein and Ogg, 1996) (Figure 7.2). The Lower Miller's Dale Lava, mistakenly referred to as Upper Miller's Dale Lava, has been radiometrically dated at this locality, with a whole-rock K-Ar age of 315 ± 12 Ma (*c*. 321 Ma with new constants) (Fitch *et al*., 1970). Fitch *et al*. concluded that this age is a close approximation to the age of hydrothermal alteration. The sill yielded a whole-rock K-Ar age of 287 ± 13 Ma (*c*. 293 Ma with new constants), which Fitch *et al*. interpreted as a minimum age of hydrothermal alteration.

Veins of fibrous material present in the sill comprise chlorite, highly altered to amesite and montmorillonoids and intimately admixed with quartz (Sarjeant, 1967).

Interpretation

Macdonald *et al*. (1984) analysed 15 samples from the Tideswell Dale Sill and provided a single representative analysis. The analyses were presented on a Zr-Nb plot that is based upon stable incompatible trace elements less prone to mobility during secondary alteration. The plot showed the presence of internal chemical differentiation in the sill, although the range of Nb and Zr abundances for the sill is small in comparison with the full range of analyses of Derbyshire basalts. The plot also showed that, with respect to Nb and Zr, the Tideswell Dale Sill is compositionally similar to both the Upper and Lower Miller's Dale lavas.

Sargent (1917) interpreted the altered vesicular lava present beneath the sill as spilitic owing to the high alkali content (greater than 6%), though Walters and Ineson (1981) considered this to be more a reflection of deuteric and hydrothermal alteration, especially during the intrusion of the sill.

The Tideswell Dale GCR site shows the effects of thermal metamorphism on the country rock adjacent to the sill. Metamorphism of the limestones is seen only beneath the sill and only where the sill directly intrudes the limestone; no marmorization has been identified where the Lower Miller's Dale Lava intervenes between the sill and the limestone. The red clay with prismatic structures beneath the sill (Figure 7.9) was interpreted by Wilkinson (in Neves and Downie, 1967) as a volcanic ash, metamorphosed as a result of sill emplacement. However, this does not explain how the ash has been so thoroughly altered to clay, whereas the lava between the clay and the sill is relatively unaffected by thermal metamorphism. It is also unusual for the effects of baking at the margins of Carboniferous sills in central England to have developed more than a few centimetres into the country rock. The prismatic structures within the red clay resemble cooling joints developed within lavas or sills, and their sigmoidal nature suggests magma flow during cooling. The absence of joints from the upper and lower parts of the clay may indicate rapidly chilled margins, with the columnar joints forming only in the more slowly cooling core of the sheet. A possible explanation of this enigmatic section is that the red clay represents a basalt lava that was thoroughly altered by humid weathering during emergence and erosion, giving an irregular upper surface, which was subsequently buried by a further lava. The sill then intruded at the level of the Lower Miller's Dale Lava, exploiting the weak layer of weathered lava.

Conclusions

The Tideswell Dale GCR site provides exposures of the Tideswell Dale Sill, which intrudes Asbian (Visean) limestones and the Lower Miller's Dale Lava, erupted around 330 million years ago. The dolerite sill appears to have been intruded preferentially along or near to the planar contact between limestones and lavas, locally exploiting the relative weakness of deeply weathered lava. The site also demonstrates several features typical of intrusive bodies, namely a reduction in grain size towards the margins of the sill, chilled margins and thermal alteration of the adjacent country rocks.

Radiometric dates suggest that the sill was intruded well after the eruption of the lavas and hence that the sill and lavas are unconnected. However, as at the **Water Swallows Quarry** GCR site, the radiometric dates may have been affected by alteration of the rocks by circulating hot fluids, resulting in anomalously young dates. Further study into the relationship between the lava and sill is required, particularly to assess their relative ages.

CALTON HILL, DERBYSHIRE (SK 119 715)

C.N. Waters

Introduction

The quarry at the Calton Hill GCR site, about 6 km east of Buxton (Figure 7.3), is noted for the presence of spinel lherzolite and harzburgite nodules within a basanite intrusion. These nodules, brought to the surface during Carboniferous volcanic activity, represent the only known examples in England of mantle-derived material, which provide insight into the petrology and geochemistry of the Earth's mantle. The **Golden Hill Quarry** GCR site in Wales is the only other location where ultramafic nodules have been found in Great Britain, outside of Scotland.

The intrusion shows a complex relationship with tuffs, agglomerates and lavas of the Upper Miller's Dale Lava, within which it has been intruded. The Upper Miller's Dale Lava is of Brigantian age, equivalent to the lava present at the **Litton Mill Railway Cutting** GCR site, and younger than the Asbian Lower Miller's Dale Lava seen at the **Water Swallows Quarry** and **Tideswell Dale** GCR sites.

The Calton Hill GCR site has been described in detail in numerous publications (Arnold-Bemrose, 1894, 1907, 1910; Tomkeieff, 1928; Aitkenhead *et al.*, 1985), although many of the sections described are no longer exposed. Miller (1988) provided an update on the condition of the site following partial infilling. Recent publications have concentrated on description of the ultramafic nodules (Hamad, 1963; Donaldson, 1978) and mineralization (Ford in Neves and Downie, 1967; Sarjeant, 1967; Curtis, 1976; Walters and Ineson, 1981).

Description

The Calton Hill Volcanic Complex has a broadly circular outcrop with a maximum dimension of about 1000 m across (Figure 7.10). The complex comprises basanite intrusions within tuffs, agglomerates and lavas of the Upper Miller's Dale Lava. The basanite is typically hard, bluish-black and relatively unaltered, whereas the lava is soft, very weathered, brown or green, and highly vesicular with chlorite infills.

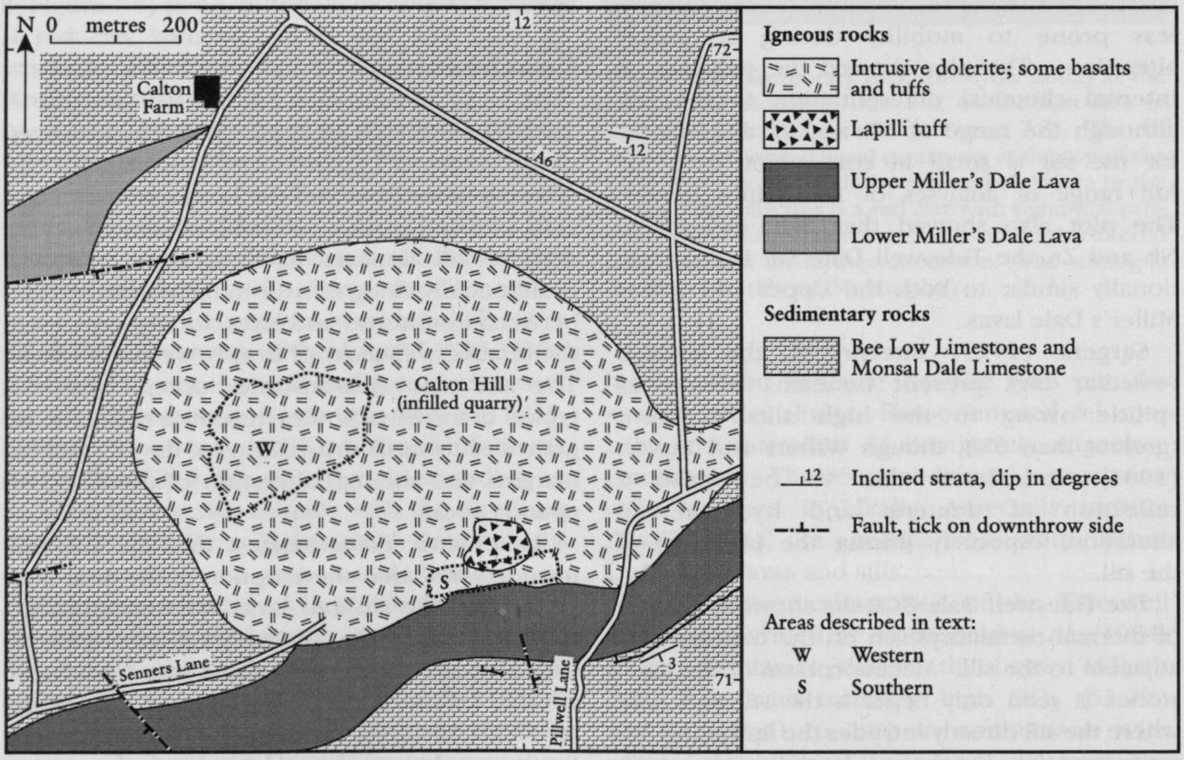

Figure 7.10 Map of the Calton Hill GCR Site. Based on Geological Survey 1:10 560 Sheet SK 17 SW (1972).

The site has been extensively quarried and progressively infilled over a prolonged period, with only two small areas left unfilled. Therefore, all descriptions have been limited to partial exposures with no single comprehensive description of the entire site. The remaining exposures that form the GCR site can be sub-divided into western and southern areas, summarized below.

Western Area (SK 1157 7137)

The south side of this area shows tongues of massive basanite, locally with columnar joints, intruding vesicular and amygdaloidal basalt. Ultramafic nodules have been found in the basanite intrusion (Miller, 1988). On the north side there are dolerite dykes up to 3.2 m wide, with good columnar joints, intruded into basalt lava. The lava is soft weathered, highly chloritized, vesicular and amygdaloidal in part with some geodes of quartz, calcite and haematite present at the contact between the two lithologies (Aitkenhead *et al.*, 1985). Oval areas of buff to greenish-grey coarse tuffs and agglomerates, containing limestone fragments up to 13 cm in diameter and basalt bombs up to 10 cm in diameter, project upwards into the lavas (Miller, 1988). A grey, calcareous, lapilli-tuff, locally bedded and graded, has also been described (Miller, 1988).

Southern Area (SK 1198 7122)

Aitkenhead *et al.* (1985) and Miller (1988) provide descriptions from different phases of quarrying; their combined descriptions provide the succession shown below.

	Thickness (m)
Basalt, very vesicular with irregular and trangressive base	*c.* 6.0
Basanite, spheroidally weathered, crudely columnar jointed with ultramafic nodules (up to 0.11 m diameter) near the base; terminates abruptly to the west at an irregular vertical contact with weathered and mineralized basalt	10.5
Basalt, heavily jointed at base, vesicular in middle and massive with some calcite mineralization at top, intruded by a thin basanite sheet with irregular upper and lower contacts	2.0
Lapilli-tuff, olive-green, calcareous; in places cross-bedded with coarser beds with pumice fragments up to 5 mm and rare bombs up to 60 mm diameter; the coarser beds are more numerous and thicker towards the top	2.5+
Limestone, dome-shaped surface at bottom of excavation	

The intrusive rock is an analcime basanite, variously described as 'analcite-basalt' by Tomkeieff (1928), 'ankaramite lava' by Donaldson (1978), 'dolerite' by Aitkenhead *et al.* (1985) and 'basanite' by Miller (1988). It generally comprises subhedral phenocrysts of olivine (Fo_{80-85}) and augite ($Wo_{45}En_{45}Fs_{10}$) in a groundmass of granular augite, plagioclase laths (An_{64}) often showing flow orientation, iron-titanium oxide, analcime and calcite with ultramafic xenoliths and xenocrysts. A representative analysis of a clinopyroxene, identified as a salite, has relatively high contents of Al_2O_3 (>4%) and TiO_2 (>1.5%) in comparison with clinopyroxenes from the Lower Miller's Dale Lava (Macdonald *et al.*, 1984).

The peridotite xenoliths occur as coarse-grained, spinel-bearing nodules (Figure 7.11) in which marginal re-equilibration of minerals occurs adjacent to the basanite (Hamad, 1963; Donaldson, 1978). Typically, the nodules are dominated by the presence of olivine (64–85%), partially serpentinized and Mg-rich (Fo_{91-92}), with subordinate orthopyroxene (8–24%) ($Wo_1En_{91}Fs_8$), minor clinopyroxene (1–2%) ($Wo_{47}En_{49}Fs_4$) and spinel (less than 4%) (Donaldson, 1978). Some nodules have been identified as harzburgites, which contain enstatite (an orthopyroxene) as the second dominant mineral, whereas the majority are lherzolites in which both enstatite and chrome-diopside (a clinopyroxene) are abundant. The nodules show extreme depletion of Ca, Al, Ti and Na relative to undepleted mantle and a high Mg/(Mg + Fe) ratio (Donaldson, 1978).

The tuffs, agglomerates and lavas of the Upper Miller's Dale Lava appear to have been deposited upon an erosion surface on top of the Asbian (D_1) Bee Low Limestones. They are in turn overlain by the Monsal Dale Limestones with faunal assemblages of the Upper *Dibunophyllum* (D_2) Zone, indicative of a Brigantian age (George *et al.*, 1976). The age of the basanite intrusion is, in contrast, poorly constrained. Fitch and Miller (1964) provided a whole-rock K-Ar date of 295 ± 14 Ma (*c.* 301 Ma with new constants) indicative of a Stephanian age of intrusion, at least 26 million years after extrusion of the lavas. This date almost certainly relates to the age of hydrothermal alteration associated with mineralization and not to the age of intrusion.

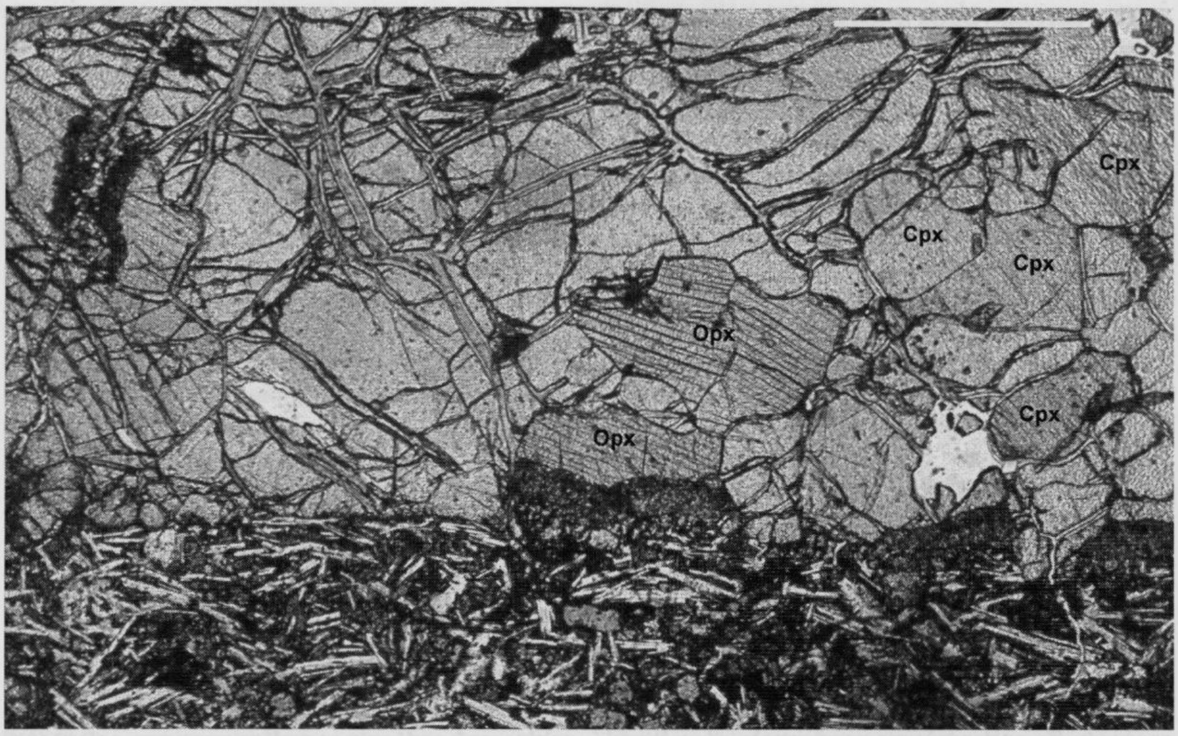

Figure 7.11 Photomicrograph of a lherzolite nodule from Calton Hill (BGS thin section No. E8340) with coarse-grained olivine, only serpentinized along fractures, subordinate orthopyroxene (Opx) and clinopyroxene (Cpx). The contact with the host basalt (bottom) is very sharp with hardly any visible reaction. Plane-polarized light. The scale bar (top right) is 1 mm. (Photo: British Geological Survey, No. MN39854, reproduced with the permission of the Director, British Geological Survey, © NERC.)

The site shows extensive development of hydrothermal mineralization. The basanite contains analcime and spherulitic chlorite, commonly filling amygdales (Aitkenhead *et al.*, 1985). Veins, 1–5 cm wide, of a fibrous mineral described by Sarjeant (1967) as chlorite, weather to form a clay mineral identified by Curtis (1976) as the smectite saponite. Ford (in Neves and Downie, 1967) has identified a complex history of mineralization including calcite, chlorite, quartz, haematite, baryte and limonite.

Interpretation

The Calton Hill Volcanic Complex was first discovered by Arnold-Bemrose (1894, 1907, 1910), who recognized an olivine basalt containing ultramafic nodules, and an agglomerate. Quarrying operations gradually revealed further the nature of the north-east part of the complex, described in detail by Tomkeieff (1928). He recognized two distinct components to the basalts: amygdaloidal Upper Miller's Dale Lava and associated stratified tuff with fragments of lava and limestone, intruded by a basanitic sill, with analcime, ultramafic nodules and showing a chilled margin against the lavas. Tomkeieff, and most subsequent workers, considered that the tuffs and amygdaloidal lavas at Calton Hill formed in a vent, which subsequently controlled the emplacement of the intrusion. The sections described by Arnold-Bemrose and Tomkeieff are no longer exposed. Aitkenhead *et al.* (1985) provided additional descriptions, broadly confirming the interpretations of previous workers.

Macdonald *et al.* (1984) provided a radically different interpretation, suggesting that the site displays five discrete lava flows in which the basanite forms the relatively unaltered centres of each flow, whilst the tops and bottoms of the flows have been extensively altered. They interpreted the Calton Hill Volcanic Complex as a phreatic tuff-ring comprising tuffs, agglomerates and flows of subaqueous lavas, which accumulated on the Bee Low Limestones, and which are separated from the overlying Upper Miller's Dale Lava by 15 m of limestone. The exposures used as evidence for this model are no longer visible. They also noted that the nodule-bearing 'lava' is silica-undersaturated, with clinopyroxene compositions consistent with the rock being alkaline. This is distinct from the tholeiitic affinities of the Lower and Upper Miller's Dale lavas.

Miller (1988) provided an update on the condition of the site following partial infilling and stated the evidence for the intrusive nature of the basanites. This includes transgressive and in places vertical contacts, chilling of the basanite margins, restriction of analcime and ultramafic nodules to the basanite, and the mineralization of the lavas. From this evidence he concluded that the basalt lavas and the basanite intrusion are parts of two distinct igneous events. He was also unable to find supporting evidence for the limestone separating the complex from the Upper Miller's Dale Lava.

Numerous publications have concentrated on describing the ultramafic nodules (Hamad, 1963; Donaldson, 1978) and mineralization (Ford in Neves and Downie, 1967; Sarjeant, 1967; Curtis, 1976; Walters and Ineson, 1981). The depletion of certain major elements and high Mg/(Mg + Fe) ratios (Donaldson, 1978) suggest that the nodules represent residues from partial melting of the mantle at an approximate depth of 45 km.

Conclusions

The quarry at Calton Hill is of international importance as the only known locality in England at which material from the Earth's mantle can be found. The material, in the form of nodules composed exclusively of minerals rich in magnesium and iron (olivine, pyroxene and spinel), probably formed in the upper levels of the mantle. Subsequently, during Carboniferous volcanic activity, fragments of this mantle material were brought closer to the surface within basaltic magma.

Around Calton Hill, an early cone of consolidated volcanic ash (tuff) and lavas that were erupted through water-saturated sediments or shallow water, is overlain by more persistent basaltic lavas of tholeiitic geochemical affinities. These Early Carboniferous volcanic rocks are intruded by basaltic sills of alkaline geochemical affinities, which are hosts to the mantle nodules. There are clearly two separate igneous events but currently available radiometric dates suggest an unrealistic time gap between the volcanic rocks and the sills. The site therefore provides opportunities for future research into the timing of these two magmatic phases, with important implications for the understanding of magmatic evolution in the Carboniferous rocks of Derbyshire.

CLEE HILL QUARRIES, SHROPSHIRE (SO 595 760)

W.J. Barclay

Introduction

The Clee Hill Quarries GCR site in Shropshire provides excellent exposures of an alkaline, olivine-dolerite sill intruded into Coal Measures strata at the Langsettian (Westphalian A)–Duckmantian (Westphalian B) boundary. The sill is variously termed the 'Clee Hills Sill' or the 'Titterstone Clee Sill'. The outcrops on Clee Hill and Titterstone Clee Hill are two of several outliers, representing remnants of a formerly extensive sheet; there are other outliers in the Brown Clee Hills. The Clee Hill Quarries GCR site is important in demonstrating the intrusive nature of the sill and its relationship with the Coal Measures strata that it intrudes. It also exhibits Pleistocene red weathering of the dolerite.

The sill is exposed in a complex of two quarries extending over an area of 1 km^2, Dhustone Quarry (SO 593 765) in the north-west and Incline Quarry (SO 596 757) in the south (Figure 7.12). A third quarry, Belfry Quarry (SO 598 765), is now back-filled with Coal Measures waste. Current workings for hard rock aggregate are in Dhustone Quarry in an area formerly covered by over 30 m of Coal Measures, the workings extending eastwards almost to Belfry Quarry. The outlier on Titterstone Clee Hill to the north was formerly worked extensively.

Field relationships indicate merely that the sill is Westphalian or later in age; it had been suggested that it may even be Tertiary until Urry and Holmes (1941) used it as a subject for early attempts at Pb-He dating and calculated an age of 135 Ma (see also **Dubh Loch** GCR site report). Subsequently Fitch and Miller (1964) determined a K-Ar whole-rock age of 295 ± 5 Ma (*c.* 301 Ma with new constants). Descriptions of the quarries were given by Pocock (1931), Marshall (1942), Toghill (1990), Turner and Spinner (1990) and Crump and Donnelly (1994).

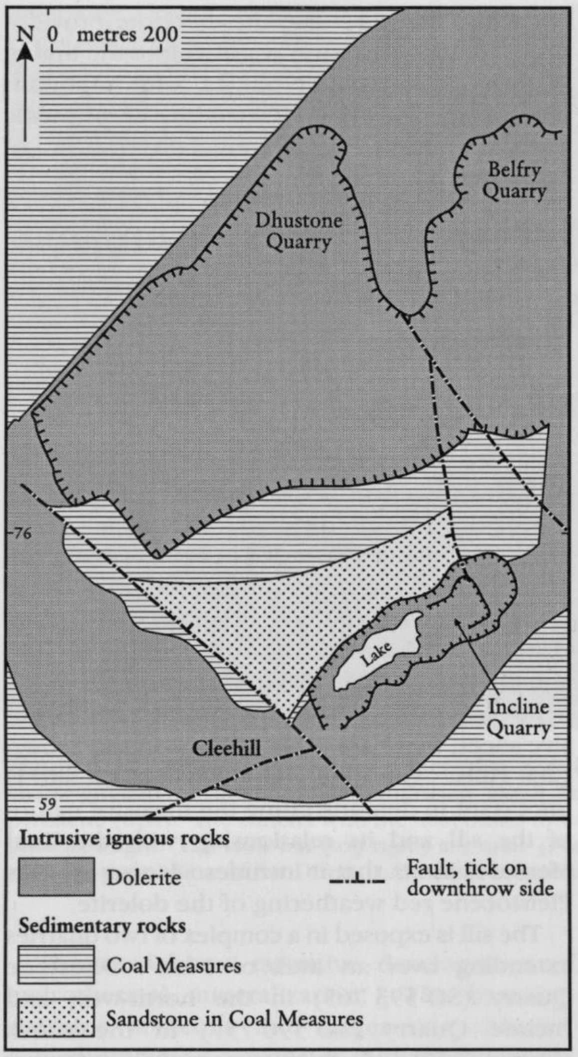

Figure 7.12 Map of the Clee Hill Quarries GCR Site. Based on British Geological Survey 1:10 000 mapping by W. Barclay (1997).

Description

The Clee Hill Quarries GCR site lies in the axial area of a NE-trending syncline occupied partly by Coal Measures strata (Dixon, 1917). The Coal Measures overlie a thin succession of unconformity-bound units, the Namurian Cornbrook Sandstone and the Dinantian Carboniferous Limestone. The sill intrudes the Coal Measures in the quarries and steps down to progressively lower levels to rest on Upper Old Red Sandstone on Titterstone Clee Hill. It is about 60 m thick, displays good columnar jointing locally and has a conchoidal fracture. Fitch and Miller (1964) noted that two sills are present, indicating multiple intrusion. Lateral offshoots of the sill into the Coal Measures, and the presence of chilled margins confirm an intrusive origin and the contact of the sill with the overlying Coal Measures is well displayed at Incline Quarry (Figure 7.13). Crump and Donnelly (1994) noted that where the sill is unprotected by a cover of Coal Measures, it is deeply weathered to an orange-red regolith, probably the product of weathering during the warm, humid interglacial periods of the Pleistocene Epoch. A diamicton that overlies the solid rocks of Clee Hill has been interpreted variously as a solifluction/gelifluction deposit (Hains and Horton, 1969) and a glacial (?Anglian) till (Crump and Donnelly, 1994).

The rock is a very hard, fine-grained olivine-dolerite, typically dark blue-grey where fresh but weathering to greenish-grey. Based on descriptions by Urry and Holmes (1941), Sabine (unpublished Geological Survey report, 1953) and Crump and Donnelly (1994), the rock consists of olivine phenocrysts set in a groundmass of plagioclase laths (bytownite-labradorite with some zoning to oligoclase) and augite, with minor magnetite, pigeonite, apatite and rutile. Analcime occurs interstitially. Olivine shows complete to partial serpentinization and some plagioclase is albitized and replaced by carbonate. A major element oxide analysis of the sill was given by Kirton (1984), who noted that the sill is nepheline-normative. Fitch and Miller (1964) dated a fresh analcime-bearing olivine-dolerite, with only slight zeolitization and minor serpentinization, from the lower of two sills on Titterstone Clee Hill.

Interpretation

Early workers (Lapworth *et al.*, 1898; Watts, 1904) interpreted the dolerite as intrusive but it was later interpreted as extrusive by Pocock (1931). Pocock's conclusion was challenged by Marshall (1942), who presented convincing evidence, now universally accepted, of the intrusive nature of the sheet. This was supported by E.B. Bailey (in discussion of Marshall, 1942), who suggested that the sill was intruded into water-logged Coal Measures sediment, a suggestion later repeated by Francis (1970a) and Kirton (1984). Turner and Spinner (1990) provided confirmation of the intrusive nature of the dolerite, with the observation that spores in the Coal Measures overlying the sill are thermally blackened. The spores date the Coal Measures

Figure 7.13 Columnar-jointed dolerite in a quarry at Clee Hills (probably Incline Quarry), taken in 1933. The section is about 25 m high, including about 6 m of baked mudstones and sandstones of the Coal Measures overlying the sill. (Photo: British Geological Survey, No. A6226, reproduced with the permission of the Director, British Geological Survey, © NERC.)

enclosing the sill as spanning the Langsettian (Westphalian A)–Duckmantian (Westphalian B) boundary, with the strata below the sill correlated with the Ra miospore biozone (equivalent to a Langsettian age) and those above with the NJ biozone (equivalent to a Duckmantian age). Given the Bolsovian (Westphalian C) age of the volcanic rocks of the West Midlands suite (see **Barrow Hill** GCR site report), the K-Ar whole-rock age of *c.* 301 Ma determined by Fitch and Miller (1964) is probably a minimum age, as suggested by Kirton (1984), and not the age of intrusion.

Conclusions

The Clee Hill Quarries GCR site provides extensive exposures of a fresh, Westphalian alkaline igneous intrusion and constitute a type locality for the West Midlands suite of sills. The sill appears to consist of more than one intrusion, and columnar jointing is well displayed in parts of the site. The intrusive relationship with the containing Coal Measures strata of Langsettian to Duckmantian (Westphalian A to B) age is demonstrable, with Coal Measures overlying the sill at Incline Quarry. As a result of temperate weathering in Pleistocene times, the sill is deeply weathered locally, with an overlying red-brown, ferruginous clay soil. The site also has historical importance as the sill was the subject of one of the earliest attempts at radiometric dating.

BARROW HILL, DUDLEY (SO 911 896)

C.N. Waters

Introduction

Barrow Hill, about 3 km west of Dudley, has been selected for its spectacular demonstration of complex inter-relationships between basalt and agglomerate of a volcanic vent, tuffs and volcaniclastic breccias deposited on the margins of the vent, and dykes of volcaniclastic material and basalt intruded into adjacent alluvial sedimentary rocks. The site is also of importance for the presence of the oldest anatomically preserved, conifer-like stems, which were buried by ash falls associated with eruptions from this volcanic centre.

The Barrow Hill Complex represents one of numerous small outcrops of igneous rocks of Westphalian age distributed widely across the West Midlands. The Barrow Hill GCR site is notable as it demonstrates explosive volcanic activity, whereas all the other outcrops, including the **Clee Hill Quarries** GCR site, are dolerite intrusions with no evidence of having reached the surface. The Barrow Hill GCR site occupies two disused quarries at Barrow Hill, described by Whitehead and Eastwood (1927) and Marshall (1942; 1946), and a clay pit located at Tansey Green, described by Galtier *et al.* (1992) and Glover *et al.* (1993).

Description

The Barrow Hill GCR site comprises a volcanic vent, located at Barrow Hill (SO 917 896), and volcaniclastic deposits at Tansey Green Clay Pit (SO 910 896) (Figure 7.14). The vent has a maximum dimension of about 400 m, broadly parallel to SW-trending faults, which mark the north-west and south-east margins of the vent. The volcaniclastic deposits occur interbedded with alluvial mudstones and sandstones of the Etruria Formation, which dip locally up to 30° to the south-west. These deposits are cut by several normal and reverse faults.

The Etruria Formation is of Bolsovian (Westphalian C) age (approximately 311 Ma according to Claoué-Long *et al.*, 1995) (Figure 7.2). The vent breccias and dolerite intrusions, which were emplaced in the lower part of the Etruria Formation, show such striking petro-

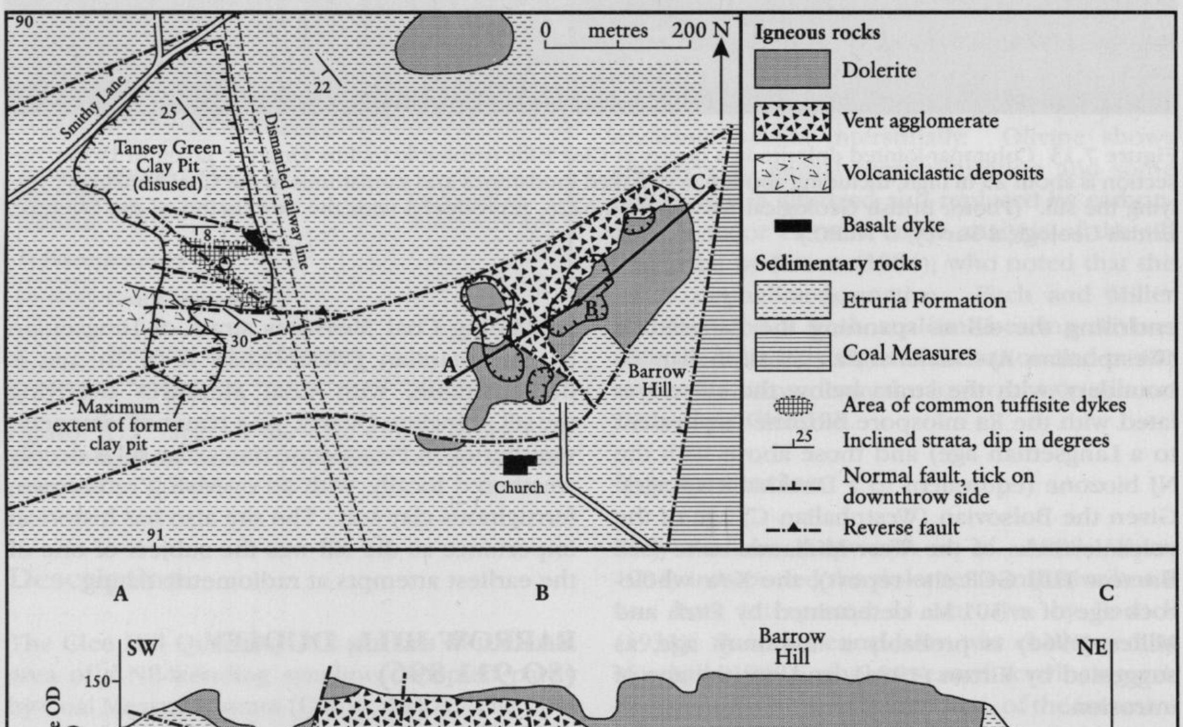

Figure 7.14 Map of the Barrow Hill GCR Site. After Glover *et al.* (1993); and British Geological Survey 1:10 000 Sheet SO 98 NE (1989). Cross-section from Marshall (1946).

graphical similarities to, and are so near to, the volcaniclastic deposits that the two are undoubtedly linked genetically and are of the same age. A K-Ar whole-rock date of 308 ± 10 Ma (*c*. 314 Ma using new constants) determined on a dolerite from Barrow Hill probably represents a close minimum for the true intrusive age (Fitch *et al*., 1970).

Barrow Hill Vent

The quarries at Barrow Hill expose a fault-bound volcaniclastic breccia, very weathered and yellow-brown with large blocks of Etruria Formation and Coal Measures mudstones, coal clasts (up to 30 cm), rounded masses of basalt and rounded quartzite pebbles (up to 10 cm) in a tuffaceous matrix containing shards. Basalt forms pipe-like, markedly transgressive and commonly fault-bound intrusions within the vent agglomerates and the Etruria Formation country rock (Marshall, 1942, 1946). In the upper part of the main quarry (SO 9149 8958) a 1–2 m-thick sill extends from the basalt pipe and intrudes the adjacent vent agglomerate. The overall geometry of the intrusion has been complicated by post-intrusive faulting (Figure 7.14).

The basalt is typically fine grained and microporphyritic, containing abundant xenoliths. An example of an analcime-bearing olivine basalt was described in detail by Marshall (1946). Feldspar microphenocrysts, typically labradorite ($Ab_{35}An_{65}$) but with more sodic rims, are up to 0.5 mm in diameter. They commonly occur clustered around serpentinized olivine crystals up to 0.7 mm in diameter, or as single crystals showing flow alignment. The groundmass comprises small laths of labradorite-andesine ($Ab_{50}An_{50}$ to $Ab_{60}An_{40}$) showing flow alignment, granular and prismatic augite, granular magnetite and some interstitial analcime. A coarser-grained variation of this is characterized by the presence of relatively few xenoliths, a greater proportion of analcime, more prominent flow alignment of feldspar laths, and locally tends toward a sub-ophitic texture. Towards the contacts of the intrusion the basalt is generally finer grained with phenocrysts up to 0.3 mm in diameter, and markedly heterogeneous, in part due to the very abundant, minute xenoliths.

Coal Measures and Etruria Formation xenoliths up to 4.5 m in diameter are numerous. The smaller clasts (up to 0.4 m) are typically rounded and highly altered with a glassy appearance, whereas the larger blocks, which tend to be present in the lower part of the exposed mass, are rounded or irregular and show rims of alteration, 0.6 m to 0.9 m wide (Marshall, 1942, 1946).

Veins of calcite, chlorite, quartz, chalcedony and haematite are common, and calcite and chlorite infill vesicles in the dolerite at the margins of the intrusion (Marshall, 1946).

Tansey Green volcaniclastic deposits

A stratigraphical section from Tansey Green Clay Pit, recorded by Glover *et al*. (1993), is shown below.

	Thickness (m)
Volcaniclastic breccia, poorly sorted, faintly bedded in lower part; contains beds rich in bombs of amygdaloidal basalt (especially near the base) and beds with abundant lithic fragments of Coal Measures and Etruria Formation (up to 1.5 m long); tuffaceous matrix with scoriaceous textures and fresh glomeroporphyritic plagioclase, angular quartz grains, carbonate nodules, lithic fragments	*c*. 30.0
Tuffaceous mudstone and siltstone, green-grey, finely laminated with small-scale asymmetric folds; lacks in-situ conifer stems	0.4
Lapilli-tuff, scoriaceous, centimetre-scale parallel lamination, plagioclase laths commonly glomeroporphyritic, feldspar microlites and sub-angular grains of volcanic beta-quartz; sharp based with conifer stems in growth position	0.6

The conifer stems present in the lapilli-tuff are 5 mm to 15 mm in diameter and up to 250 mm in length, occurring with a vertical or near-vertical orientation (Galtier *et al*., 1992). The stems are partly converted to coaly material (fusain) with the outer bark commonly absent.

Both the volcaniclastic deposits and the underlying Etruria Formation are cut by discordant tuffisite veins (Figure 7.15), ranging from millimetres to 0.2 m in thickness. The veins are generally orientated parallel to the dominant east–west and north-west–south-east fault trends. They are composed predominantly of fragments of probable Coal Measures origin, in particular quartz grains, coal, plant fragments, carbonaceous siltstone and sideritic nodules. Sparse, rounded clasts of altered basalt similar to those seen in the volcaniclastic breccia are also present. The veins may show alignment of clasts

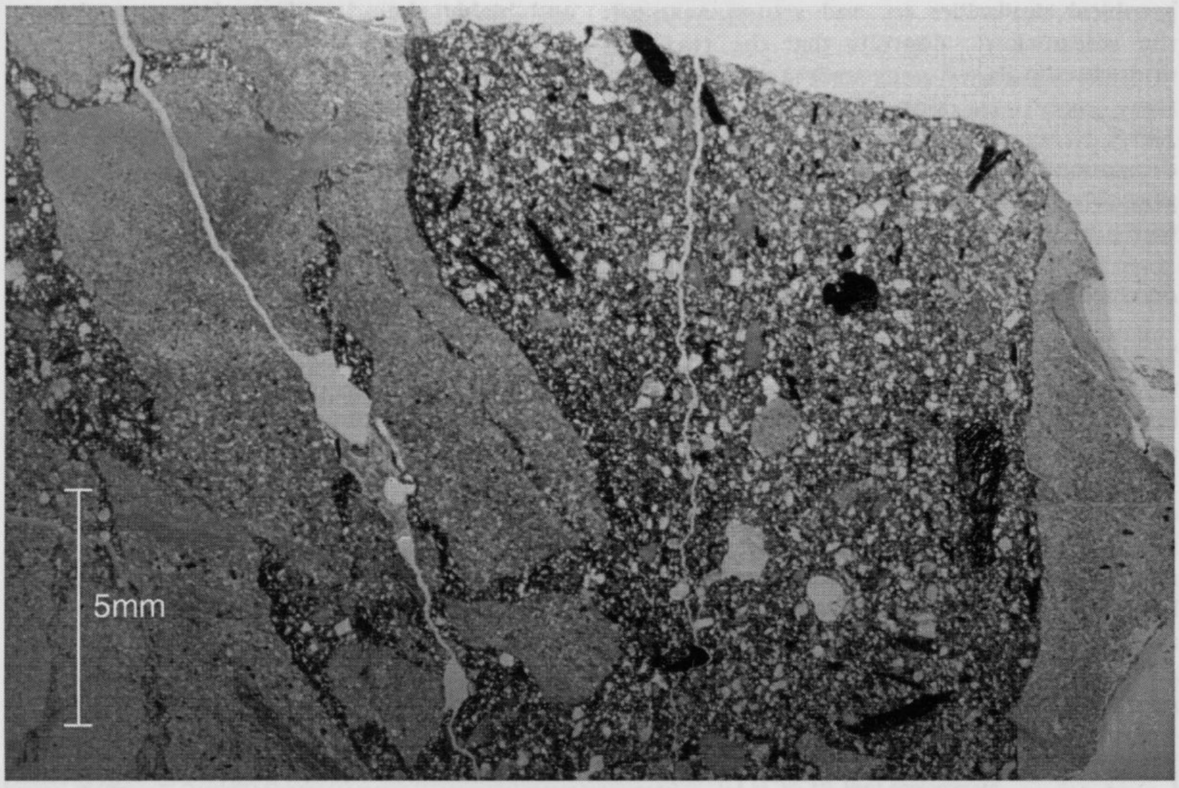

Figure 7.15 Photomicrograph showing details of a tuffisite vein cutting through mudstones, from Tansey Green Clay Pit, Barrow Hill. Grain alignment occurs parallel with the vein and grain size decreases toward the vein margin. Plane-polarized light. (Photo: from Glover *et al.*, 1993.)

parallel with the dyke wall and a broad decrease in grain size from the centre to the margins. Associated with the tuffisite veins is a single agglomerate pipe, up to 10 m in diameter, and a NW-trending alkali basalt dyke, approximately 0.3 m wide. The agglomerate pipe contains rounded clasts similar in composition to the tuffisite veins, although with a greater abundance of basaltic clasts. The basalt dyke is extensively altered to chlorite and calcite, though it displays a relict ophitic texture. Amygdales of chlorite and calcite are common, being larger and more abundant towards the margins of the dyke.

Interpretation

The presence of igneous rocks at Barrow Hill was first recorded by Jukes (1859), though reference was made only to the presence of a mass of basalt. Whitehead and Eastwood (1927) suggested that the basalt has a laccolithic form, intrusive into the lower part of the Etruria Formation. The first detailed descriptions of the Barrow Hill intrusion were provided by Marshall (1942, 1946), in which the vent-like geometry was established and the presence of abundant country-rock xenoliths was recorded. The volcaniclastic rocks became well exposed as a consequence of excavations at Tansey Green Clay Pit. Galtier *et al.* (1992) described the volcaniclastic deposits in the context of their importance in preserving delicate conifer-like stems. A more thorough description of these deposits and associated volcaniclastic and basaltic intrusions was provided by Glover *et al.* (1993).

The complex of agglomerates and dolerite intrusions present at Barrow Hill are interpreted as a vent, with the igneous rocks in some cases intruding along pre-intrusion or penecontemporaneous faults (Marshall, 1942, 1946). The basalt pipes and vent agglomerates are thought to be near coeval. The country rock appears to have been relatively wet and unlithified at the time of intrusion, suggesting emplacement at or near the penecontemporaneous ground surface (Glover *et al.*, 1993). The surface expression of the vent is not preserved but is thought to have been a tuff-cone.

Glover *et al.* (1993) provided a complex history of evolution of the volcaniclastic deposits developed marginal to the vent. The lapilli-tuff, which formed the first volcanic material erupted from the vent, is interpreted as ash fall that accumulated rapidly in an alluvial floodplain environment, with each laminae representing a distinct pulse. Temperatures were sufficient to char the conifer stems, removing the outer cuticle (bark) layer (Galtier *et al.*, 1992). This charring can result from an initial hot, gaseous, base surge, which precedes the passive fall of lapilli-tuffs from a convective turbulent cloud. The tuffs were succeeded by tuffaceous mudstone and siltstone, in turn followed by highly explosive, gaseous, phreatomagmatic eruptions, which deposited the volcaniclastic breccia. The absence of impact craters beneath large clasts in the breccia may suggest that the deposit had undergone some reworking as debris flows, though the preservation of delicate euhedral plagioclase crystals and glomeroporphyritic texture suggest that the breccias could not have been transported far from the volcanic source.

The tuffisite dykes and the agglomerate pipe are interpreted as the product of phreatomagmatic activity. Interaction of hot, gaseous magma and groundwater resulted in the explosive vaporization of the water and the fragmentation of the country rock, with a rapid upward migration of gas, transporting fragments of Coal Measure material and injecting them into the overlying Etruria Formation. The tuffisite dykes, agglomerate pipe and basalt dyke probably represent lateral feeders from the main Barrow Hill Complex. The orientation of the tuffisite and basalt dykes parallel with the main faults in the area, suggest that emplacement of the complex occurred coeval with a phase of extensional faulting.

Conclusions

The Barrow Hill GCR site is nationally important for the spectacular demonstration of the relationship between a volcanic vent and adjacent volcanic deposits erupted from that vent around 307 million years ago. The vent comprises a breccia of igneous and sedimentary clasts intruded by basaltic rocks, which contain abundant fragments and blocks of Upper Carboniferous sedimentary rocks. The level of erosion seen in the vent at Barrow Hill appears to be at or near to what was the ground surface at the time of eruption. Hot, gassy magma penetrated wet and largely unconsolidated sediments, and the interaction with groundwater resulted in explosive activity in which dykes of sedimentary and igneous material were forced underground for some distance marginal to the vent. The surface expression of the explosive activity is seen as ash-fall deposits, hot, gaseous lateral surge deposits and a thick breccia, similar in composition to that present in the vent.

The ash-fall deposits preserve the oldest anatomically preserved conifers found to date. The excellent preservation of the wood, pith and xylem make these stems of considerable importance in the understanding of the evolution of gymnosperms and provides constraints on the environment of growth of conifers during the Carboniferous Period.

MIDDLE HOPE, NORTH SOMERSET (ST 322 659–ST 350 670)

V.P. Wright and P.J. Cossey

Introduction

The Middle Hope GCR site, a large coastal site near Weston-super-Mare and about 4 km north-east of the **Spring Cove** GCR Site, provides a Courceyan to Chadian section extending from the Black Rock Limestone through to the Gully Oolite. The section includes an exceptional development of the Middle Hope Volcanic Beds with undersea lavas and pyroclastic deposits. The section has been described by Geikie and Strahan (1899), Morgan and Reynolds (1904), Sibly (1905), Reynolds (1908, 1917), and more recently by Matthews *et al.* (1973), Speedyman (in Savage, 1977), Jeffreys (1979), Whittaker and Green (1983) and Faulkner (1989b). The following account is based mainly on the work of Faulkner (1989b). Details of the lava geochemistry are to be found in Faulkner (1989a).

Description

The Lower Carboniferous succession on the Middle Hope peninsula (see Figure 7.16a) includes 97 m of the Black Rock Limestone, 30 m of the Black Rock Dolomite and 10 m of the Gully Oolite (Faulkner, 1989b). The principal feature of interest is the Tournaisian Middle Hope Volcanic Beds (also known as the Woodspring Lava and Tuff). These volcanic beds,

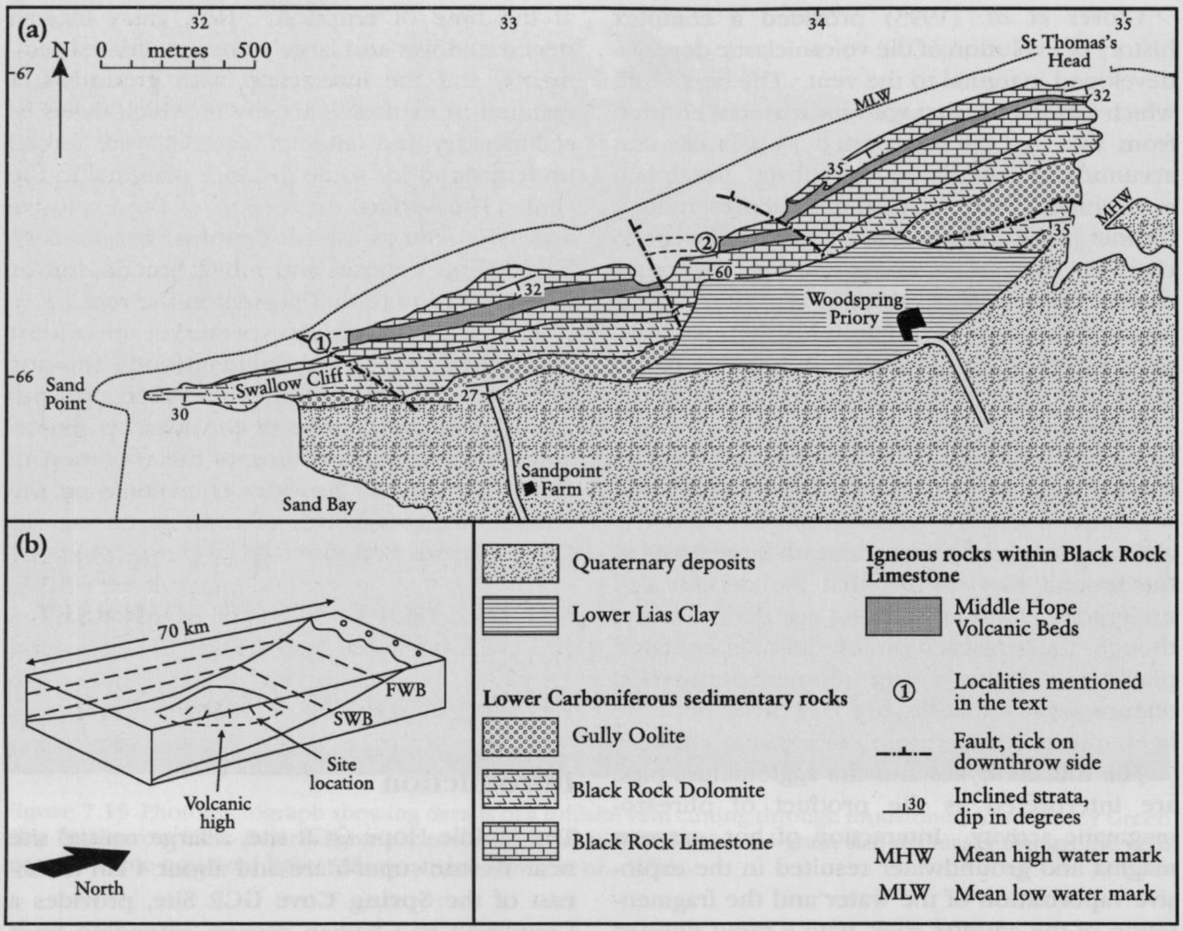

Figure 7.16 (a) Map of the Middle Hope peninsula illustrating the position of localities referred to in the text (1 = Swallow Cliff (ST 3245 6605); 2 = 700 m WNW of Woodspring Priory (ST 337 664)). (b) Schematic model of the volcanic high responsible for the formation of the Middle Hope Volcanic Beds (FWB = fair-weather wave base; SWB = storm-wave base). Modified after Faulkner (1989b).

4–37 m thick, occur within the Black Rock Limestone, lying entirely within the *Polygnathus communis carinata* biozone of Groessens (1976) and the *Caninophyllum patulum* assemblage biozone of Ramsbottom and Mitchell (1980). Additional biostratigraphical information relating to this part of the succession, including detail of the distribution of conodonts, corals and brachiopods, is given by Whittaker and Green (1983).

The Middle Hope Volcanic Beds crop out at several locations on the northern side of the Middle Hope peninsula (see Figure 7.16a). They are best examined in two small bays, one at the eastern end of Swallow Cliff (ST 3245 6605) and the other 700 m WNW of Woodspring Priory (ST 337 664) (localities 1 and 2 in Figure 7.16a). Details of the succession are illustrated in Figure 7.17.

The lower part of the Black Rock Limestone, below the volcanic rocks, consists of decimetre-scale, bioturbated wackestones and packstones, with fissile and marly layers. The fauna consists of crinoids, brachiopods, and rugose and tabulate corals. Trace fossils include *Zoophycos*, *Chondrites*, *Planolites* and *Thalassinoides*-like burrows. This is overlain by a unit of multi-coloured tuffs, which coarsens upwards. Lapilli-rich layers, 3–5 cm thick, within this unit also increase in grain size upwards. Bioclastic material of marine origin is present in these tuffs. Associated with the tuffs are thin-bedded limestones, some planar stratified or showing symmetrical ripples. The multi-coloured tuffs are in turn overlain by a unit of green, graded and ungraded lapilli-tuffs, with clasts of devitrified

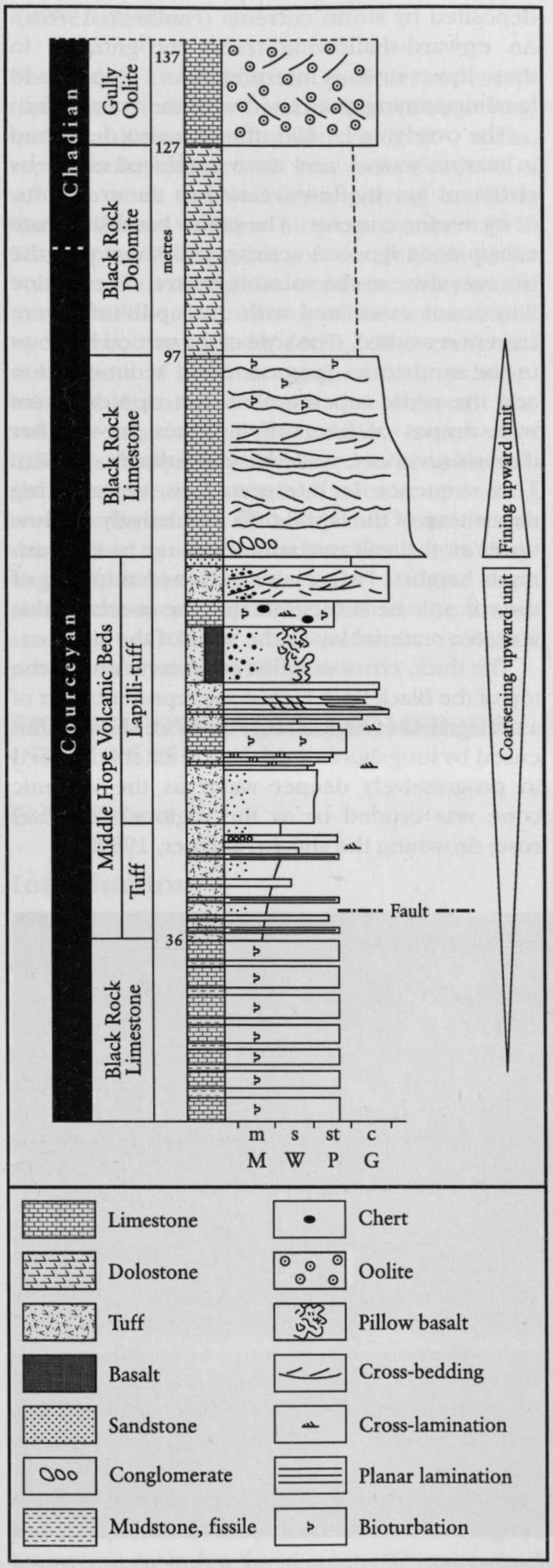

Figure 7.17 Generalized sedimentary log of the Lower Carboniferous succession at the Middle Hope GCR site. The vertical scale is non-linear; figures are metres above base of section. Horizontal scale indicates grain size: (m = mudstone; s = siltstone; st = sandstone; c = conglomerate; M = mudstone (calcareous); W = wackestone; P = packstone; G = grainstone). After Faulkner (1989b).

amygdaloidal basalt and unidentified chloritized rock, mixed with marine bioclastic material (Figure 7.18). Calcite vein networks are prominent locally. Within the ungraded lapilli-tuffs there are matrix- and clast-supported conglomerates, with clasts of chert nodules and limestones. Also associated with the lapilli-tuffs are bioclastic limestones and both cross-stratified and laminated sandstones (Figure 7.19). The latter have abundant small vertical burrows ('pipe rock') associated with the brachiopod *Lingula mytiloides* (Faulkner, 1989b). Within the lapilli-tuffs is a prominent, laterally impersistent basaltic pillow lava. At Swallow Cliff, the lava ranges in thickness from 3.5 m to 4.3 m. The basalt is very weathered with abundant calcite-filled amygdales up to 10 cm across. The upper surface is very irregular and highly amygdaloidal.

The Middle Hope Volcanic Beds thin laterally from 37 m at Swallow Cliff in the west, to 4 m in the east of the site (ST 348 669). They are overlain erosively by the upper part of the Black Rock Limestone, which comprises a fining-upwards, cross-stratified bioclastic grainstone unit (24 m thick) with a conglomerate at its base and a gradational top contact with the overlying Black Rock Dolomite. Faunal evidence presented by Whittaker and Green (1983) indicates the presence of a significant non-sequence at the top of the Black Rock Dolomite after which the Gully Oolite was deposited. The Gully Oolite is a massive cross-bedded oolite, fossiliferous and partly dolomitized in its lower part.

Interpretation

The lower matrix-rich limestones at the base of the Black Rock Limestone represent deposits formed in the outer part of a sloping, shallow marine shelf (Figure 7.16b), below storm-wave base (Faulkner, 1989b). The lower tuff unit records the onset of volcanic activity, which increased in intensity with time, producing the coarsening-up trend. The lapilli-rich layers in this unit indicate periods of more energetic eruptions. Associated limestones were probably

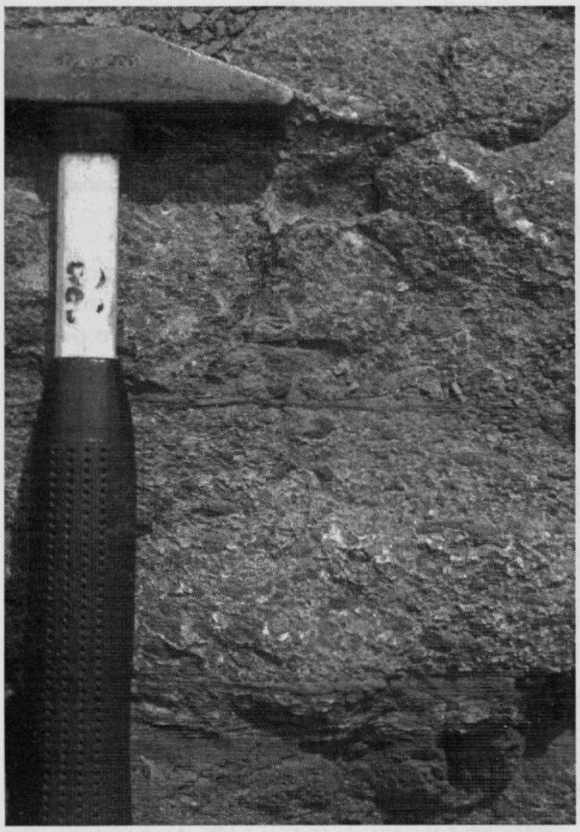

Figure 7.18 Graded lapilli-tuffs in the Middle Hope Volcanic Beds. The hammer shaft is about 35 cm long. (Photo: P.J. Cossey.)

deposited by storm currents (Faulkner, 1989b). An upward-shallowing trend recognizable in these lower units is interpreted as a response to local updoming associated with the volcanicity.

The overlying lapilli-tuffs were also deposited in marine waters, and were emplaced either by sediment gravity flows related to the eruptions, or by marine currents. The pillow basalts indicate subaqueous igneous activity, and show that the site was close to the volcanic centre. The marine limestones associated with the lapilli-tuffs were current reworked. The style of the vertical burrows in the sandstones suggests rapid sedimentation and the cyclic repetition of thin rippled layers with drapes of fine tuff indicates fair-weather deposition above wave base (Faulkner, 1989b). This sequence is interpreted as representing deposition of the lapilli-tuffs in relatively shallow water as the volcanic cone built up to its maximum height. Progressive eastward thinning of the volcanic beds suggests that the source of this volcanic material lay to the west of the site.

The thick, cross-stratified grainstone unit at the top of the Black Rock Limestone represents part of a transgressive, high-energy offshore shoal, influenced by longshore or tidal currents that formed in progressively deeper water as the volcanic cone was eroded or as the regional sea level rose, drowning the shoal (Faulkner, 1989b).

Figure 7.19 Graded and cross-bedded lapilli-tuffs, interbedded with limestones in the Middle Hope Volcanic Beds. The hammer shaft is about 35 cm long. (Photo: P.J. Cossey.)

Conclusions

The Middle Hope GCR site provides an exceptional section of Tournaisian (Courceyan) marine limestones and volcanic rocks, representing the growth and subsidence of a volcanic cone on the outer part of an Early Carboniferous shallow-sloping marine shelf. The repeated exposure of the Middle Hope Volcanic Beds along the northern shoreline of the site allows the anatomy of the volcanic pile to be reconstructed in detail. The combined association of sedimentological and palaeontological features indicates that although the volcanic high was initially below storm-wave base, it subsequently developed in progressively shallower water as a result of volcanic updoming and the formation of a volcanic cone, which came close to sea level before finally subsiding. Together these features make Middle Hope one of the most important sites for the understanding of Early Carboniferous volcanic processes in southern England.

SPRING COVE, NORTH SOMERSET (ST 310 625)

C.N. Waters

Introduction

The Spring Cove GCR site, a coastal section north of Weston-super-Mare, has been selected as a representative of Arundian (Dinantian) extrusive igneous rocks from southern England. Submarine pillow lavas display an intimate association with adjacent carbonate rocks and the section provides excellent exposures of the Dinantian succession from the top of the Gully Oolite, through the Caswell Bay Mudstone, to the Birnbeck Limestone, for which Spring Cove is the type locality (Figure 7.20).

The presence of igneous rocks in the Weston-super-Mare district has long been known, though uncertainty as to their intrusive or extrusive nature was not resolved until the descriptions of Geikie and Strahan (1899). Numerous publications provided descriptions of the lavas (Boulton, 1904; Strahan and Cantrill, 1912; Reynolds, 1917; Speedyman in Savage, 1977), culminating in the detailed lithological and petrographical descriptions in the Geological Survey memoir for the district (Whittaker and Green, 1983).

Sibly (1905) showed that the volcanic rocks of the Weston-super-Mare district occur at two distinct stratigraphical positions, estimated to be about 145 m apart (Whittaker and Green, 1983). The lower, Middle Hope Volcanic Beds, described in the **Middle Hope** GCR site report, have subsequently been shown to be Courceyan in age, and the higher volcanic rocks, which include the Spring Cove Lava, are Arundian (George *et al.*, 1976). Whittaker and Green (1983) have demonstrated that the Spring Cove Lava is approximately contemporaneous with lavas and tuffs from the Bristol district at Goblin Combe, Broadfield Down, Cadbury Camp and Tickenham, and that the volcanic activity occurred over a relatively wide area and included several small vents.

Description

The Spring Cove GCR site comprises a lava about 15 m thick with an exposed length along-strike of about 140 m (Figure 7.20). It occurs within the Birnbeck Limestone, which contains corals and brachiopods indicative of an early Arundian age (Whittaker and Green, 1983). The lava has a gently undulating contact with the underlying limestone and the strata dip at about 25° to 35° to the south.

The critical stratigraphical section at Spring Cove (see below) is derived from a composite section logged by G.W. Green (Geological Survey 1:10 560 map ST 36 SW, 1967) and reproduced by Whittaker and Green (1983).

	Thickness (m)
Birnbeck Limestone	
Limestone, reddish-fawn, dolomitized but with relict cross-bedding and corals; tuffaceous debris in lower 1.5 m, increasing towards the base	9.7
Spring Cove Lava	
Olivine basalt, typically fine grained, chocolate-brown, massive and highly amygdaloidal with imperfect pillow structures and red oolitic limestone fragments in all stages of alteration and assimilation, which in places appear to occupy spaces between pillows (Figure 7.21). In the centre of the exposure, cindery lava is mixed with broken limestone fragments. Calcite veins are common throughout. The base is irregular and channelled up to 1.2 m into the underlying limestone	*c.* 15.0
Birnbeck Limestone	
Limestone, red and grey, very massive, dolomitized, but with relict cross-bedding, ooliths, corals and crinoid debris	up to 12.0

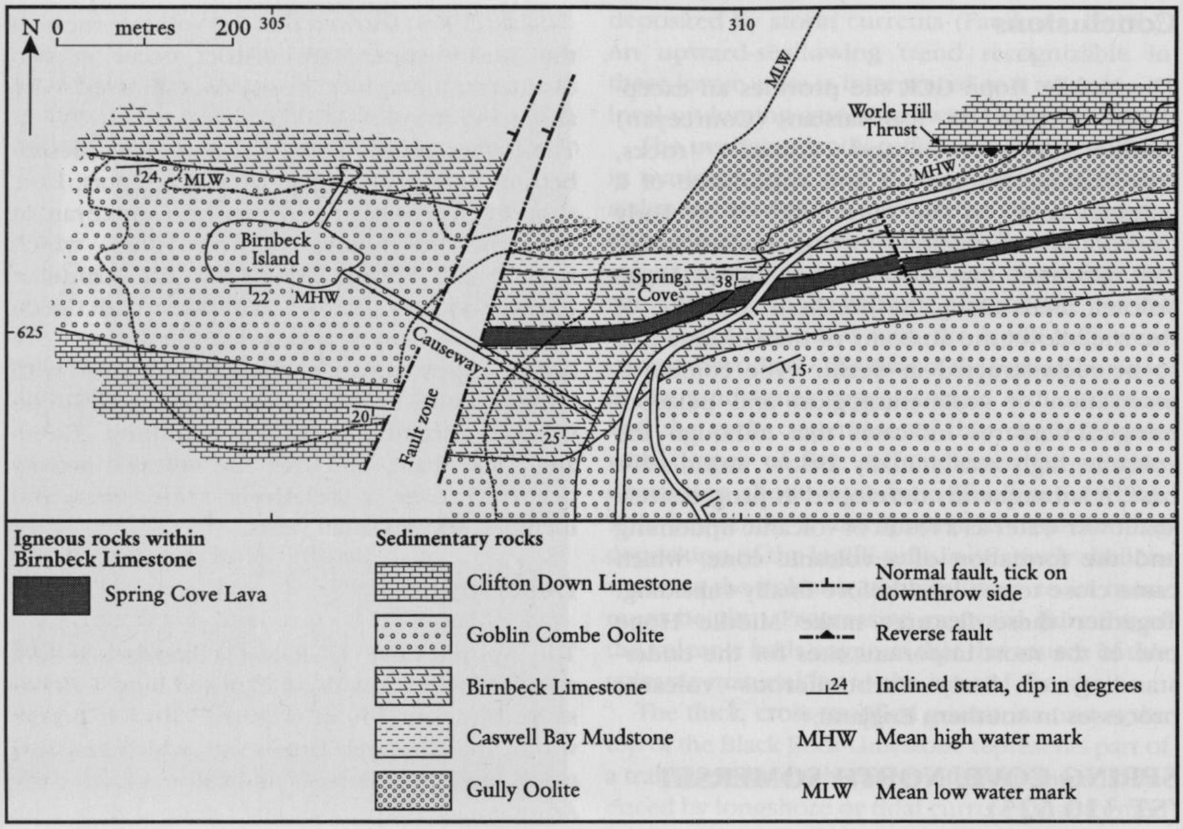

Figure 7.20 Map of the Spring Cove GCR Site. After Whittaker and Green (1983).

Boulton (1904) described a progressive variation in the lava. To the north-east a 27 m section was described as a relatively uniform 'pillowy' basalt, brecciated and amygdaloidal with large masses of limestone. The pillows are best developed at the base of the lava, where they have a diameter of 1 m or more. To the south-west of this an 18 m-long exposure was described by Boulton as tuff or agglomerate with masses of highly slaggy basalt, 1.5–1.8 m long, and lumps of limestone, often very fractured, up to 3.7 m in length. Speedyman (in Savage, 1977) described one 'agglomeratic tuff' cutting obliquely across the lava. In this body, the larger blocks of limestone and rounded pillows of basalt are commonly closely spaced and are elongate parallel to the margins. The matrix comprises densely packed angular fragments of basalt and has a planar fabric that is deformed around the blocks. The 'agglomeratic tuff' is overlain locally by basaltic pillow lavas with rare irregular 'agglomeratic' zones. The remaining approximately 100 m of section was described as hard, massive, purplish-brown, slightly amygdaloidal olivine basalt with pseudomorphs after olivine (Boulton, 1904; Speedyman in Savage, 1977). Pillows and rare blocks of limestone up to 0.3 m across occur in this basalt.

Petrographical details for the lava and adjacent sedimentary rocks were provided by Whittaker and Green (1983). The basalt contains olivine and possibly augite phenocrysts, up to 3 mm in length, showing slightly corroded euhedral outlines, though totally pseudomorphed by calcite and a clay mineral. The groundmass comprises microlitic feldpars, forming laths rarely longer than 0.8 mm, which are highly altered and show a swirling flow alignment. The groundmass is deeply stained by ferric oxide. Morgan and Reynolds (1904) and Reynolds (1917) described a 'variolitic', or spherulitic glassy basalt, but Whittaker and Green (1983) described this as a finely mottled pale-red and dark-reddish-brown scoriaceous rock and were unable to identify any evidence of spherules (varioles). They did, however, describe ovoid vesicles filled with iron-stained calcite and vermicular clay aggregates.

Figure 7.21 Basaltic pillow lava at the Spring Cove GCR site with clasts of altered limestone and numerous calcite veins (ST 309 625). The hammer shaft is about 35 cm long. (Photo: British Geological Survey, No. A11792, reproduced with the permission of the Director, British Geological Survey, © NERC.)

The section is notable for the presence of reddened oolitic limestone for 12 m below the lava, which is not observed in this part of the succession elsewhere in the district. The limestone contains iron-stained, sub-angular to rounded pumice fragments, which are generally devitrified and replaced by a clay mineral or carbonate. Some pumice fragments and other clastic fragments display oolitic coatings. An unusual feature of the limestone is the presence of authigenic orthoclase, which has developed in micrite pellets and ooliths in the tuffaceous limestones. Ashy particles have also been noted up to 2.4 m above the lava (Morgan and Reynolds, 1904). These have been described by Whittaker and Green (1983) as comprising sub-rounded argillized fragments of fine-grained basalt in a matrix of sparry calcite.

Reynolds (1917) published two chemical analyses for the 'variolitic' basalts at Spring Cove, noting low Na_2O (0.72 and 1.10%) and very high K_2O (5.01 and 4.93%) contents.

Interpretation

The internal structure of lenticular sheets of lava, tuff and agglomerate, sloping to the south, as described by Boulton (1904), was used by him to suggest the presence of a vent to the north.

The complex relationships between pillow lavas, tuffs and agglomerates suggest that the section shows more than one lava. The pillow structures, for which this site is of importance, are indicative of subaqueous eruption, and hence Reynolds (1917) interpreted the lavas as spilites, but he did note the low sodium and very high potassium contents, which are atypical of spilites. In a review of Carboniferous basalts in the Bristol district, Dearnley (1960) observed that the more highly vesicular and altered the rock, the higher the total alkali content and the lower the Na:K ratio. He concluded that the petrographical and geochemical characteristics are indicative of late-stage autometasomatism by alkali-rich residual fluids rather than as a result of interaction of magma with seawater to produce spilites, as proposed by Reynolds, and this interpretation was accepted by Whittaker and Green (1983).

The irregular shape of limestone fragments present within the lava in various stages of alteration and assimilation (Figure 7.21) and the slightly undulating and cross-cutting relationship of the lava with underlying limestones, led Boulton (1904) and Whittaker and Green (1983) to suggest that the lava was extruded onto sediments that were not fully consolidated. The 'tuffs and agglomerates' were interpreted by Speedyman (in Savage, 1977) as an autobreccia, possibly formed as a result of a submarine slide of pillow lavas with included clasts of limestone. These deposits were subsequently over-ridden by further pillow lavas.

Red-stained limestones present above the lava contain highly altered basalt fragments, which are interpreted as the erosion products of the underlying lava. The limestones immediately beneath the lava contain pumaceous material, which is interpreted not as primary ash-fall material but as the product of reworking and re-sedimentation. Oolitic coatings to some pumice fragments suggest that the pumice had undergone some marine transport and the growth of authigenic orthoclase before the final development of the oolitic coating suggests that high concentrations of potassium were present in the environment of limestone deposition (Whittaker and Green, 1983). The red iron staining of the limestone is generally considered to be due to the weathering of the tuffaceous material present (Geikie and Strahan, 1899; Whittaker and Green, 1983), though Morgan and Reynolds (1904), Boulton (1904) and Reynolds (1917) had disputed this interpretation. Both the iron and the potassium were probably derived from fragments of lava and volcanic glass as a product of leaching following re-sedimentation in an enclosed basin where concentrations of the leached material could occur (Whittaker and Green, 1983).

Conclusions

The Spring Cove GCR site represents Lower Carboniferous (Visean) volcanic rocks of south-west England, in a well-exposed and easily accessible section. It demonstrates fine examples of pillow lavas and brecciated lavas, formed when magma is erupted under water, in this case probably on the seabed.

The complex lava flow was extruded during a period of dominantly marine carbonate deposition. The lava was preceded by limestone containing reworked fragments of earlier pumice. The weathering of this volcanic material during and soon after deposition produced a distinctive red colouration to the limestone. This carbonate deposit was not fully consolidated when it became buried by the lava. As a result the lava has an undulating base and contains an abundance of irregularly shaped limestone blocks. The subsequent return to carbonate deposition is marked by the presence of further limestones above the lava. These limestones are also reddened due to the presence of fragments of basalt eroded from the underlying lava flow.

GOLDEN HILL QUARRY, MONMOUTHSHIRE (ST 4308 9709)

R.E. Bevins

Introduction

An understanding of the mineralogy and chemistry of the Earth's lower crust and upper mantle is provided mainly by the study of xenoliths brought to the surface by magmas. The nature of the lithosphere in southern Britain is poorly understood, owing to the dearth of mantle and lower-crustal xenolith occurrences, in contrast to the area to the north of the Iapetus Suture (see chapters 2, 4 and 5). The supposed volcanic diatreme pipe at Golden Hill Quarry, in the county of Monmouthshire, along with a nearby associated dyke at Glen Court (ST 4036 9824), is of national importance as it represents one of only two occurrences of mantle-derived xenoliths in southern Britain, the other being at **Calton Hill**, Derbyshire (see GCR site report).

The first account of the Golden Hill Quarry diatreme pipe was by Boulton (1911), who provided a petrographic account of the igneous rocks, and described the presence of a dyke or plug, containing augite and biotite megacrysts and probable ultramafic nodules, all contained in a monchiquitic groundmass. This study was based on the rather poor exposures available at that time. Subsequent quarrying in the late 1940s and early 1950s provided much better exposures, particularly of the contacts, precipitating the report by Cox (1954).

A more complete description of these more extensive exposures was provided by Eyles and Blundell (1957) who reported that in fact the majority of the igneous material at the quarry is agglomeratic, and that this was the site of a volcanic vent, cut by a monchiquite dyke. Eyles and Blundell also provided critical evidence for the age of the volcanic activity. Welch and Trotter (1961) gave a further account of the petrography of the monchiquite, while Upton *et al.* (1983) referred to the presence at Golden Hill Quarry of carbonated and/or hydrated biotite-rich ultramafic xenoliths (probably biotite pyroxenites), biotite megacrysts and tectonized quartz-plagioclase xenoliths. Finally, Haslett (1992) compared the petrography of the Golden Hill Quarry monchiquite with a similar rock exposed at Glen Court, 3 km to the WNW.

On the basis of stratigraphical evidence, combined with the age of blocks contained in the diatreme pipe at Golden Hill Quarry, the magmatism is thought to be Early Carboniferous in age (Eyles and Blundell, 1957). There is scattered evidence for Carboniferous igneous activity across a wide area in southern Britain, and the Golden Hill Quarry GCR site provides important regional information concerning the character and extent of this episode in south Wales.

Description

The Golden Hill Quarry GCR site is located to the north-east of Great House Farm (Figure 7.22), some 7 km south-east of Usk. The quarry, now disused, is some 100 m in diameter and up to 15 m deep. It contains an agglomeratic facies and a NW-orientated dyke, cutting through sandstones (Brownstones) of Devonian age (Figure 7.23). Aeromagnetic data suggest that the overall form of the intrusion is pipe-like, with a total surface area of no more than 900 m^2. The host rock is a monchiquite.

The most complete description of the Golden Hill Quarry agglomerates and the monchiquite intrusion, however, lies in the unpublished work of D.T. Moffat, which is included in part in the account below.

The dyke is exposed only at the southern margin of the quarry (*c.* 10% of the outcrop area). It consists of a melanocratic, dark-grey, fine-grained, xenolithic, amygdaloidal monchiquite. In thin section this rock is seen to possess a groundmass comprising laths of plagioclase and pyroxene, rare biotite and minor ?analcime and magnetite, along with euhedral microphenocrysts of olivine and clinopyroxene (now replaced by chlorite-like phases, carbonate or serpentine) all set in abundant, partially devitrified glass. Included xenoliths, which make up 5–15% of the rock, comprise sedimentary wall-rock, tectonized quartz-plagioclase rocks, and ultramafic lithologies, in addition to mafic megacrysts (Figure 7.24), typically in the range 0.4–4 cm. All are of similar character to those present in the agglomeratic facies (see below).

The agglomerate comprises fragments of the monchiquitic dyke (70–80%) along with sedimentary wall-rock, tectonized quartz-plagioclase rocks, ultramafic xenoliths (10–25%) and mafic megacrysts (3–15%), contained in a clay- and carbonate-rich ochreous matrix with scattered quartz crystals. The clasts are rounded, oblate ellipsoid to spherical in shape, and range in size from 0.5 cm to 15 cm. Within the pipe, Moffat (unpublished manuscript) noted a number of petrographically distinct subunits, although each is massive, unstratified and lacking obvious sorting.

The monchiquitic fragments (up to 5 cm across) are virtually identical to the monchiquite of the dyke (see above). The wall-rock fragments comprise chiefly sub-angular to rounded, red to green, fine- to medium-grained sandstones, red-brown mudstones and micaceous sandstones, reaching a maximum size of 150 cm. In addition, however, Eyles and Blundell (1957) reported the presence of various lithologies of Visean and Tournaisian age.

The quartz-plagioclase xenoliths are small (0.5–2 cm) in size and rare (less than 1% of all xenoliths). They comprise medium-grained

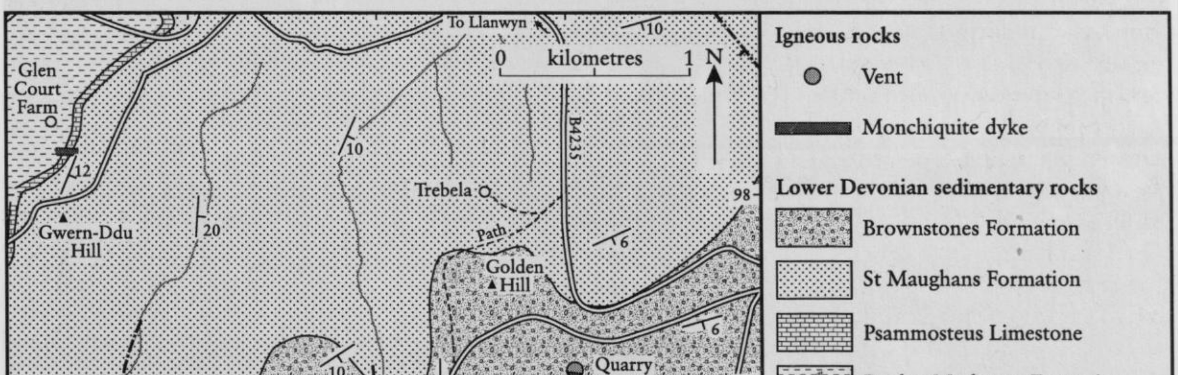

Figure 7.22 Map of the Golden Hill Quarry GCR site. Based on Geological Survey 1:50 000 Sheet 250, Chepstow (1972).

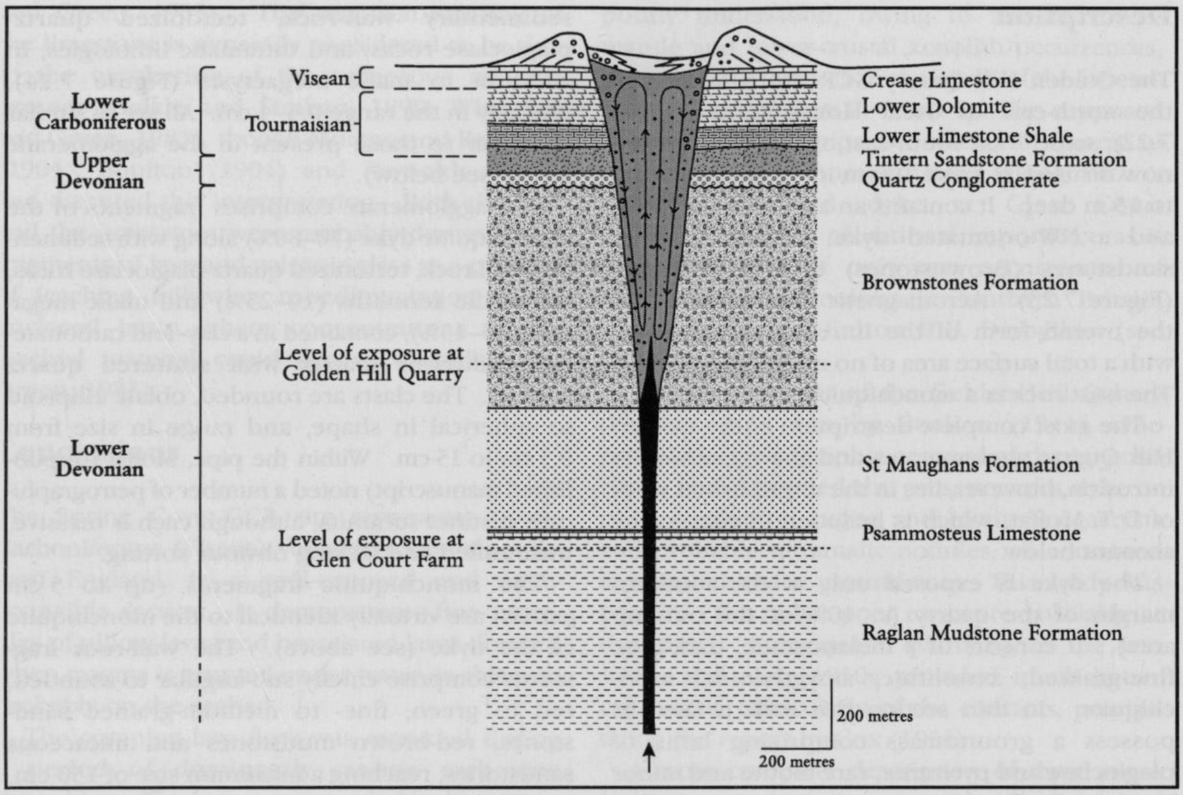

Figure 7.23 Schematic representation of the diatreme pipe, sub-diatreme monchiquite dyke and stratigraphical relationships at the Golden Hill Quarry GCR site. After D.T. Moffat (unpublished manuscript).

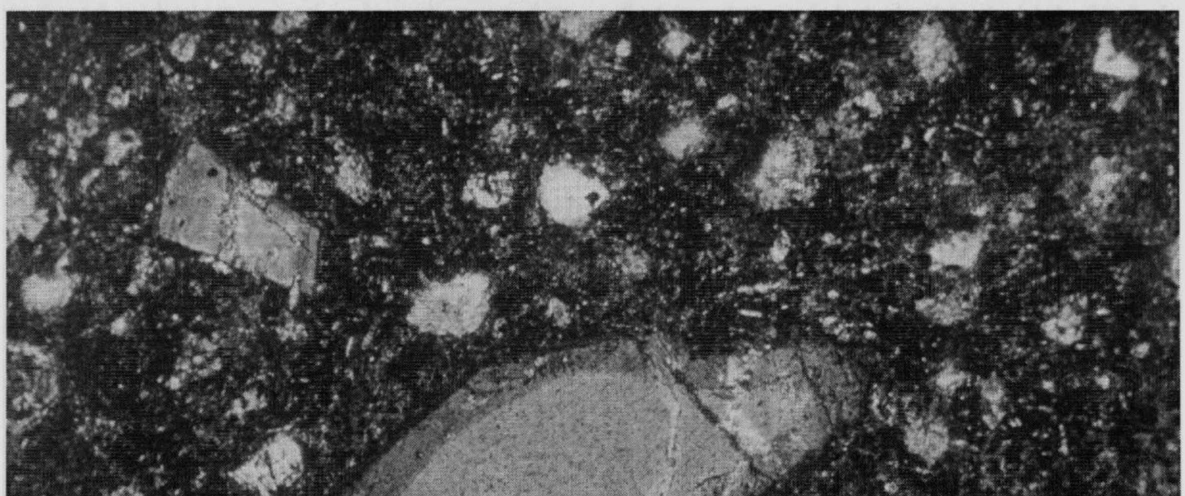

Figure 7.24 Clinopyroxene megacryst in monchiquite from the Golden Hill Quarry. The crystal is 4 mm across. Crossed polars. (Photo: R.E. Bevins.)

plagioclase porphyroclasts contained within a granular mosaic of strained quartz crystals. They are broadly tonalitic in composition.

Ultramafic xenoliths are typically rounded and are in the size range 0.5–15 cm. Investigation of the primary mineralogy of these nodules is extremely difficult due to the intense nature of alteration, with almost all the mafic phases being replaced by carbonate, serpentine and chlorite-like minerals. Originally, they appear to have been peridotites (lherzolites and harzburgites), with 62–85% olivine, 10–25% orthopyroxene, 2–12% clinopyroxene, and less than 3% chrome-spinel and minor glass (D.T. Moffat, unpublished manuscript). Original clinopyroxenes (chrome-rich diopsides) are the most common mineral to show at least partial preservation. Texturally, the majority of the ultramafic xenoliths are coarse grained (grain size in the range 0.4–1.0 cm) and show little evidence of deformation. Some xenoliths, however, show evidence of deformation, recrystallization and annealing.

Mafic megacrysts in the agglomerate, as in the dyke, comprise clinopyroxene and biotite. Clinopyroxene megacrysts typically have diameters of 1–5 cm and are subhedral to anhedral. Most are pale- to emerald-green chrome-rich diopsides, although a small proportion are black in colour and of augitic composition, the latter typically possessing lamellar intergrowths of ilmenite. Biotite megacrysts are euhedral to subhedral, dark-brown single crystals ranging between 0.5 cm and 5 cm in size. They are phlogopitic in composition.

The age of magmatic activity at Golden Hill Quarry is constrained in three ways. First, the agglomerate and dyke cut through strata of early Devonian age. Secondly, Ramsbottom (in Eyles and Blundell, 1957) identified various fossils of Carboniferous age in carbonate blocks from the agglomerate. In particular, he recorded Visean age fossils in a block of crinoidal limestone, with no post-Visean age fossils being identified, suggesting that magmatism may have occurred during Visean times. However, a K-Ar date of 336 ± 7 Ma (*c.* 342 Ma using new constants) (Fitch *et al.*, 1969) and an Ar-Ar plateau age of 347 ± 3.2 Ma (M. Timmerman, pers. comm., 2002), both on biotite megacrysts, suggest a Tournaisian or very early Visean age.

Interpretation

The earliest account by Boulton (1911) interpreted the Golden Hill Quarry igneous rocks as forming either a wide, irregular dyke or a plug, although it is clear that interpretation was hampered by poor exposure. Better exposures, resulting from more extensive quarrying, allowed Cox (1954) to propose that the intrusion has a plug-like form, and to compare it to the kimberlite pipes of the Kimberley area of South Africa. Eyles and Blundell (1957) argued that it does indeed have a pipe-like form, but is in fact a volcanic vent, comparing it with the volcanic vents exposed on the Ayrshire coast of Scotland, rather than the Kimberley-type pipes.

D.T. Moffat (unpublished manuscript) has provided the most recent interpretation, arguing that a transition from monchiquite through to agglomerate can be observed and that therefore the two facies are coeval. He took this gradation to reflect the transition from a liquid–solid dyke system to a gas–solid diatreme system. In the gas–solid system, ultramafic mantle and lower-crustal xenoliths were transported rapidly to the near surface where they were mixed with blocks from the highest crustal levels. A circulatory flow was established, witnessed by some of the incorporated blocks being preserved at up to 1000 m below their original stratigraphical position. In this circulatory system, the ultramafic xenoliths were altered by carbonitization and hydrothermal fluids.

The ultramafic xenoliths appear to represent samples derived from the upper mantle (spinel-bearing lherzolites and harzburgites), while the tectonized quartz-plagioclase lithologies are possibly from lower-crustal levels.

On the basis of stratigraphical evidence, the age of included blocks, and K-Ar and Ar-Ar dates on biotite separates, the magmatic activity appears to be Early Carboniferous, most likely Tournaisian or earliest Visean, in age. Boulton (1911) correlated the Golden Hill Quarry monchiquite with the basic intrusion cutting Devonian strata at Bartestree, near Hereford (Reynolds, 1908). Farther to the south, Carboniferous age lavas and tuffs are exposed at a number of localities to the west of Bristol (see Whittaker and Green, 1983), as at the **Spring Cove** and **Middle Hope** GCR sites. Evidence for Carboniferous volcanism in Wales is scant, however. The Mathry quartz-dolerite dyke (Cave *et* *al.*, 1989), of probable Carboniferous age, can be traced for some 40 km across south-west Wales and interestingly is approximately in-line with the Golden Hill Quarry and Glen Court occurrences. A thin dyke was also exposed in a temporary road cut at Castleton, north-east of Cardiff, cutting strata of Devonian age and presumed to be of Carboniferous age (Lawrence *et al.*, 1981), while R.A. Waters (in Institute of Geological Sciences, 1978) reported the presence of thin tuffaceous siltstones and a bentonite in the Cwrt-yr-Ala borehole a short distance to the west of Cardiff. What makes correlation difficult, however, is that none of these sites contain lamprophyric rocks of the type seen at Golden Hill Quarry and Glen Court.

Conclusions

The Golden Hill Quarry GCR site exposes a volcanic pipe and an associated dyke-like intrusion of probable Early Carboniferous age. The intrusion is of an unusual rock-type termed 'monchiquite', and the pipe is infilled with a coarse deposit, which contains a variety of exotic blocks as well as large individual crystals of magmatic origin. The exotic blocks derived from the wall-rock, along with stratigraphical relationships between the pipe and surrounding country rocks, provide age constraints for the igneous activity. The site is most important, however, because of the presence of a variety of ultramafic rocks that originated in the Earth's mantle and quartz-plagioclase rocks that probably came from the lower part of the Earth's crust. These have been carried to higher crustal levels by rising magma and occur as blocks and fragments (xenoliths) in both the pipe and the intrusion. This is one of only two sites in southern Britain where mantle-derived xenoliths are known to occur, and hence is of national importance in providing an insight into the character of the mantle beneath this area.