Precambrian Rocks of England and Wales

J.N. Carney[1], J.M. Horák[2], T.C. Pharaoh[1], W. Gibbons[3]

D. Wilson[1], W.J. Barclay[1], R.E. Bevins[2]

Palaeontology Chapter by

J.C.W. Cope[3], T.D. Ford[4]

Other contributors

E.W. Johnson[1], K.A. Jones[5], A.J. Reedman[1] and N.H. Woodcock[6]

[1] British Geological Survey, Keyworth, Nottingham, UK
[2] Department of Geology, National Museums and Galleries of Wales, Cardiff, UK
[3] Department of Earth Sciences, Cardiff University, Cardiff, UK
[4] Department of Geology, University of Leicester, UK
[5] School of Construction and Earth Sciences, Oxford Brookes University, Oxford, UK
[6] Department of Earth Sciences, Cambridge University, Cambridge, UK

GCR Editor: **L.P. Thomas**

JOINT NATURE CONSERVATION COMMITTEE

British Geological Survey

Chapter 4

Malvern Hills

W. J. Barclay and T. C. Pharaoh

INTRODUCTION

The Malvern Hills collectively form one of the largest of the English Precambrian sites. They provide comprehensive exposures of a heterogeneous calc-alkaline igneous complex, and of a younger volcanic succession, and are consequently a rare window into the early geological history of southern Britain. The hills also bear spectacular testament to the effects of Variscan orogenic forces well to the north of the main Variscan deformation front (see the front cover of this volume). The hard, resistant nature of the rocks results in them forming high ground, here rising to 425 m. The hills comprise a narrow ridge about 12 km long, the 9 km^2 outcrop being divided into seven major, fault-bounded blocks (Figure 4.1). All the blocks, except those forming the Tinker's Hill–Broad Down–Hangman's Hill area, are dominated by rocks of the meta-igneous Malverns Complex; Broad Down comprises the volcanic rocks of the Warren House Formation.

The excellent exposures, mostly in quarries, have stimulated much research, including pioneering petrological and geochemical studies. Timins' work published in 1867 was one of the first attempts to study the major element geochemistry of a group of rocks. Rutley's study published in 1888 was one of the first systematic descriptions of the petrography of British plutonic rocks. The strongly layered nature of many of the Malverns Complex rocks led some early workers to suggest that they were paragneisses, formed by the metamorphism of sedimentary rocks (e.g. Horner, 1811; Holl, 1865; Rutley, 1887; Groom, 1899, 1900, 1910). Phillips (1848) and Callaway (1889, 1893) considered them to be of entirely igneous origin, a view later vindicated by Lambert and Rex (1966), Lambert and Holland (1971), Wright (1969) and Thorpe (1982). The Malverns Complex is thus now considered as being largely a heterogeneous, igneous and meta-igneous association of rocks derived by progressive ductile and brittle shearing, and accompanying metamorphism, of

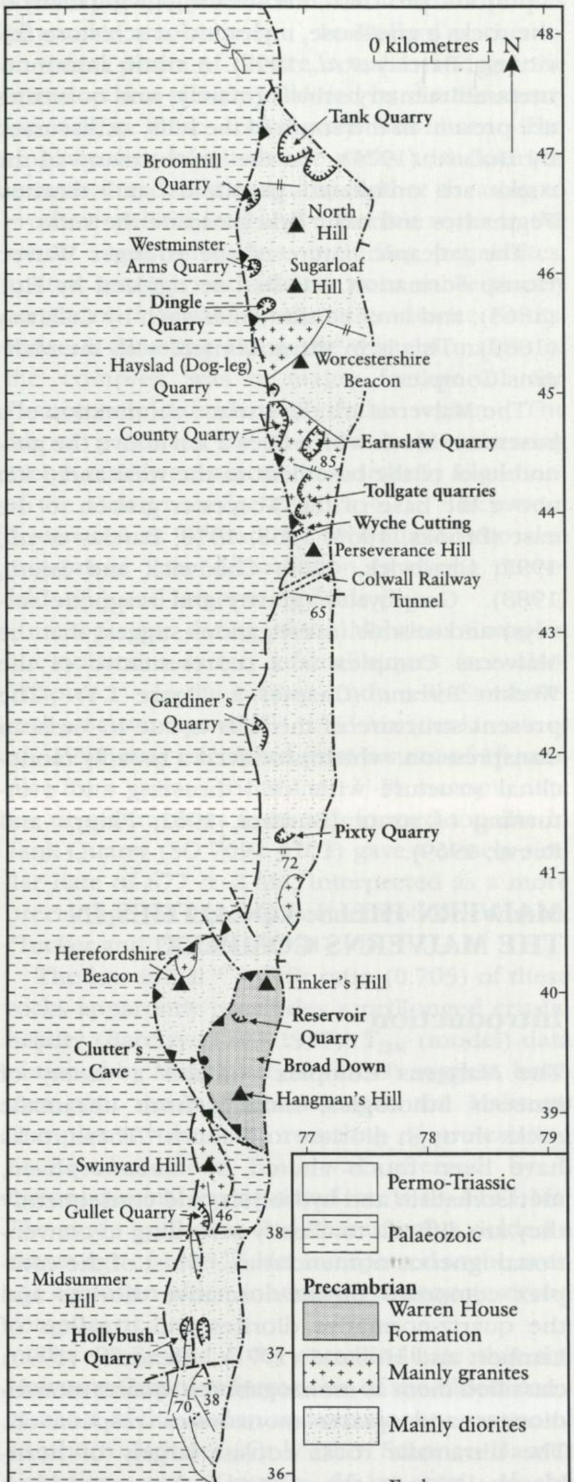

Figure 4.1 Geological map of the Malvern Hills site, with main localities shown by bold lettering. Note that locally the granites and diorites are strongly foliated with schistose to gneissose fabrics developed. The map includes structural information from R. A. Strachan (pers. comm.) and Bullard (1975).

a plutonic protolith, the shearing giving many of the rocks a gneissose, mylonitic or schistose fabric (e.g. Barclay *et al.*, 1997). A minor amount of metasedimentary schists (mainly) and quartzites are present in the south of the hills, as discussed by Bullard (1975). In the north, many of the rocks are unfoliated granitoids and diorites. Pegmatites and basic dykes intrude the suite.

The volcanic nature of the younger Warren House Formation was first recognized by Holl (1865), and later confirmed as such by Callaway (1889). This is in thrust contact with the Malverns Complex.

The Malverns are the surface culmination of a basement block which rises 2 km above the general level of the basement to the west and 3 km above the base of the Worcester graben to the east (Brooks, 1963, 1968, 1970; Barclay *et al.*, 1997; Chadwick, 1985; Chadwick and Smith, 1988). Geophysics (gravity and magnetic surveys) and seismic investigations suggest that the Malverns Complex is a representative of the Wrekin Terrane (Chapter 1; Figure 1.1). The present structure of the hills is due to Variscan transpression, which produced a broadly monoclinal structure with local thrusting and overturning of strata (Butcher, 1962; Phipps and Reeve, 1969).

MALVERN HILLS: LOCALITIES IN THE MALVERNS COMPLEX

Introduction

The Malverns Complex contains a variety of igneous lithologies, ranging from ultramafic rocks through diorites to granites. These rocks have been much altered by metamorphism, metasomatism and hydrolysis, and consequently they are difficult to classify according to conventional igneous nomenclature. Most of the complex comprises olivine-normative diorites and the quartz-normative diorites and tonalites of Lambert and Holland (1971). Dearnley (1990) classified them as monzogabbros, quartz monzodiorites and quartz monzonites respectively. The ultramafic rocks consist largely of hornblende, lying in the gabbro and monzogabbro groups of the IUGS classification. The relatively minor proportions of felsic rocks are represented by the granites, which range from monzogranites through syenogranites to alkali-feldspar granites and rarer quartz-rich granitoids (Dearnley, 1990).

Geochemical analysis provides the most appropriate tool to determine the origins and intrusive settings of the rocks, by comparing stable elements that survived the multi-episode tectonothermal history with their occurrence in igneous rocks formed in modern environments. Geochemical studies are described in Lambert and Holland (1971), Dearnley (1990) and Barclay *et al.* (1997). They show that the Malverns Complex is typical of calc-alkaline arc magmatic suites, with a signature characterized by low Nb and Ti, lack of Fe enrichment and strong enrichment of certain LIL elements and Th. A later suite of Precambrian microdiorite intrusions, seen at some of the localities to be described, is part of a different magmatic phase. These sheets show similarly strong enrichments of LIL and Th, but exhibit Fe enrichment and only moderate depletion of Nb. In these respects they show a within-plate chemical character, and thus more closely resemble basaltic andesites of the Uriconian Group (Barclay *et al.*, 1997) exposed in Shropshire (Chapter 5). Still younger sheets of microdiorite are emplaced into the adjacent Ordovician strata and have also been found within the Malverns Complex itself.

In many exposures a penetrative foliation is present, locally giving the plutonic protolith a schistose or superficially gneissose appearance. Phyllonitic and mylonitic rocks are also present, associated with ductile shear zones, but the intensity of deformation in the northern Malvern Hills is, in general, less than farther south (Worssam *et al.*, 1989). Mafic and ultramafic rocks are present in minor amounts. Granite occupies the north-western and southern slopes of Worcestershire Beacon, exhibiting a complex relationship to the diorite host (Bullard, 1975, 1989). It is also present in smaller intrusive bodies and sheets elsewhere. Discordant pegmatites post-date most of the ductile deformation, as do mafic bodies on the eastern slopes of North Hill and Worcestershire Beacon. Thin sheets of microdiorite are also discordant to the ductile foliation of the complex.

The most detailed petrography of the complex is that of Lambert and Holland (1971). Diorites and tonalites form about 75 per cent of the outcrop, typically comprising green hornblende and tabular plagioclase (andesine). Relict igneous textures showing interlocking and ophitic feldspar laths and plates, zoned plagioclase feldspars and pseudomorphs after olivine are found in a few specimens of the more mafic diorites (Dearnley, 1990). Accessory minerals include sphene (titanite), apatite and zircon. With increasing grade of deformation and metamorphism, epidote and chlorite replace hornblende, and oligoclase is progressively sericitized, ultimately producing the rock type referred to as epidiorite by Blyth and Lambert (1970) and Lambert and Holland (1971). The range of dioritic rocks is most easily demonstrated in the North Hill quarries (SO 769 470; 771 469; 772 468). Ultramafic rocks, consisting largely of hornblende with subsidiary biotite, are found in small amounts in many of the quarries, most notably at Lower Tollgate Quarry (SO 770 442). Some of the ultramafic rocks may have a cumulate relationship to the more chemically evolved rocks, others forming from hybridization reactions (Lambert and Holland, 1971). Massive, well-jointed, pink granite is exposed in Earnslaw (SO 771 445) and Tollgate quarries, although minor bodies and sheets are very widespread. The granites typically contain tabular microcline, oligoclase and biotite (< 10 per cent); small amounts of muscovite, iron-rich epidote, chlorite and iron oxides make up the remainder, particularly in the more deformed examples, which also exhibit quartz aggregates and small irregular feldspar aggregates. The granites are variably foliated, ranging from virtually undeformed through to quartzo-feldspathic mylonites. A well-developed lineation is commonly present on some foliation surfaces.

Pegmatites are abundant throughout the complex, ranging from diffuse streaks in diorite to sharply discordant, dyke-like bodies. Potassic (microcline-quartz), sodic (albite-quartz) and granitic varieties have been recognized (Lambert and Holland, 1971). Muscovite is the principal accessory, together with minor amounts of biotite, secondary chlorite and epidote. Emplacement of granitic and pegmatitic bodies into the complex resulted in modification by hybridization and metasomatism. Blyth and Lambert (1970) have documented extensive hybridization between diorites and felsic melts. Metasomatism, involving the elements Na, Ca, K, Mg, Fe and Ti, is most clearly demonstrable in the ultramafic protoliths, such as the biotite amphibolites. A small, alkaline, potash-rich intrusive body of trachytic composition is present in Earnslaw Quarry.

The history of intrusion and deformation of the complex that was proposed by Bullard (1975) followed Brammall and Dowie (1936) in advocating the presence of two distinct phases of granite emplacement. In Bullard's scheme, an initial phase of diorite, tonalite and granite intrusion was closely followed by ductile shearing whilst these rocks were still hot. The emplacement of ultramafic rocks and dolerites next occurred, succeeded by further shearing to produce well-foliated and mylonitic rocks in the south. Acid intrusions, including pegmatites, aplites, granites and felsites were subsequently emplaced, followed by the microdiorite sheets. Variscan thrusting along the western margin of the complex was a major feature of the Phanerozoic deformation of this region. The fabrics produced by the two major shearing events mainly cut across the northerly alignment of the Malverns ridge (Figure 4.1). They were designated as 'S_1' and 'S_2' by Bullard, who also recognised later deformation involving microfolds (F_3) and larger-scale folds (F_4).

Isotopic age dating of the Malverns Complex has utilized a variety of techniques (see also, Chapter 1). In the earliest study, a Rb-Sr whole-rock isochron age of 681 ± 53 Ma (Beckinsale *et al.*, 1981) was calculated from a suite of 16 samples from various locations. U-Pb isotopic data for zircon fractions from a deformed tonalite in Tank Quarry (SO 7691 4701) gave a closely similar date of 677 ± 2 Ma, interpreted as a more precise age for the emplacement of the complex (Tucker and Pharaoh, 1991).

The low initial $^{87}Sr/^{86}Sr$ ratio (0.705) of these rocks apparently precludes a prolonged crustal history (Barclay *et al.*, 1997). T_{DM} (model) data obtained by Murphy *et al.* (1999) suggest, however, that magma generation in the Malverns Complex involved the recycling of pre-existing crustal basement that was affected by a tectonothermal event dated at 1043–1147 Ma. The study by Tucker and Pharaoh also yielded a zircon age of 1598^{+30}_{-32} Ma, interpreted as the average age of an older, inherited Proterozoic zircon component.

The Rb-Sr and U-Pb dates indicate that the Malverns Complex forms one of the oldest components of the Avalonian accretionary terrane of southern Britain. Only the Stanner–Hanter Complex, near Kington, 55 km west of the Malverns (see Hanter Hill site report, Chapter 5), which has yielded an Rb-Sr isochron age of 702±8 Ma (Patchett *et al.*, 1980), is likely to be older.

Strachan *et al.* (1996) have published age determinations relevant to the recryztallisation history of the complex. They show that ^{40}Ar-^{39}Ar mineral cooling ages determined from hornblende in metadiorite intrusions constrains the timing of upper greenschist to low amphibolite facies thermal reactivation of the complex to between 649 and 652 Ma; this gives a maximum age for the shearing. Hornblende from a diorite that is net-veined by late pegmatites, which in turn crosscut the mylonitic shear fabrics, yields an age of 610 Ma. This is interpreted to date static thermal rejuvenation associated with pegmatite intrusion and it constrains the minimum age of the shearing. A plateau age of about 597 Ma recorded from muscovite in a greisen vein in granite dates the hydrothermal alteration of the complex.

Locality Descriptions

There are numerous large quarries in the Malverns (Figure 4.1) but none is totally representative of the complete range of rocks present. A selection of the more important localities is therefore given and these are interpreted collectively in a later section. Further descriptions are given by Penn and French (1971), Bullard (1989) and Barclay *et al.* (1997).

Tank (North Hill) Quarry (SO 768 469)

Also known as North Malvern or Pyx Quarry, this exposes mainly hybrid pink and green diorites with some granites. It is one of the most spectacular of the Malvern quarries, forming a notch in the north-eastern slope of North Hill. Originally much deeper, with its walls rising 80 m above the quarry floor, it has been partly infilled with domestic waste.

The rocks are foliated granites and diorites, with an abundance of shear zones in which the igneous protolith is retrogressively metamorphosed to amphibolite and biotite schist. The most prominent foliation is approximately vertical and strikes north-west. Epidote and haematite are common in joints and veins and there are numerous pinkish red, almost flat-lying very coarse-grained pegmatite and fine-grained aplitic veins. The meta-igneous rocks are intruded by microdiorite dykes, one of which was chemically analysed and found to belong to the younger Precambrian magmatic episode mentioned earlier in the introduction to the Malverns Complex. Exposures on the west face show a transition from unfoliated diorite to foliated, gneissose diorite containing xenolithic schlieren of gneissose amphibolite. Reaction between the amphibolite and diorite is shown by the presence of coarse appinitic patches in the diorite and by intimate mixing of the lithologies. The quarry thus provides a good example of the relationships between the principal lithologies and the later intrusion of microdiorite dykes and pegmatites (Bullard, 1989; Penn and French, 1971).

A geology trail at the entrance to the quarry illustrates representative lithologies. Most of the faces are inaccessible and dangerous. Exposures are found along the lower wall of the north-western face, but at the time of writing, rampant growth of *Buddleia* bushes has made them inaccessible at all but a few points. A metal ladder down the west slope of the quarry infill gives access to the most westerly of the lowermost exposures. Descending the metal steps, one is confronted by a steeply dipping, NW-trending shear surface in a protolith of broadly dioritic composition. To the south, lineations on the surface plunge moderately to the south; to the north slickensides plunge to the north, indicating a complex history of movement. Halfway between the steps and the north-western end of the quarry, the epidote-veined, feldspathized and hybridized diorite host is intruded by a steeply inclined, NW-trending granite sheet. This has a diffuse, locally banded contact with the diorite on its south side, but a sharp, intrusive contact on its north side, suggesting multiple intrusion. Coarser pegmatite is also apparently intruded into the sheared diorite. Late, flat-lying, 0.15 m-thick pegmatite veins cross-cut all the lithologies. Farther to the north, the diorite is cut by a late (? Variscan) fault zone up to 0.3 m wide, filled with breccia and calcite, and dipping 40° to the NNW.

Dingle Quarry (SO 7654 4567)

Dingle Quarry provides a safe, easily accessible locality at which to examine age relationships between some of the Malverns Complex lithologies, which include the gently dipping microdiorite sheet (probably Precambrian) shown in Figure 4.2. A 4 m-thick dolerite dyke forms a prominent step in the quarry. Below this, the dyke truncates granite veins in metadiorite. The

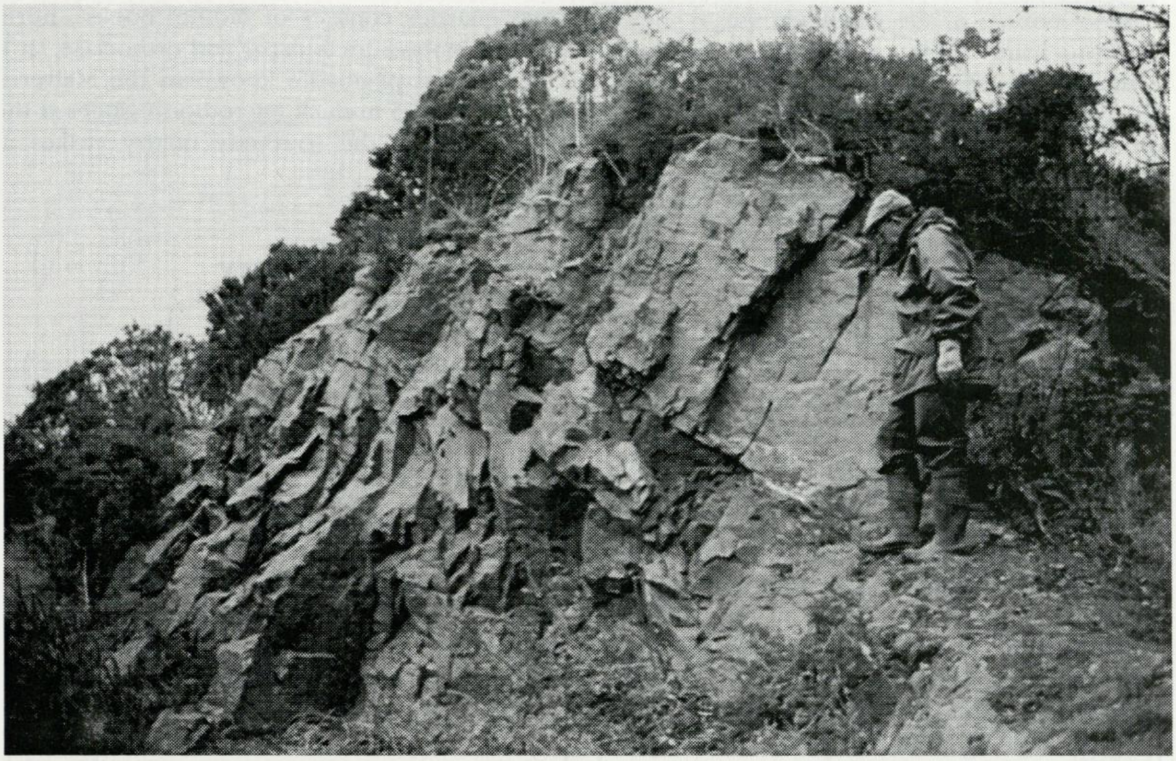

Figure 4.2 Exposure at Dingle Quarry showing contact of a microdiorite sheet intrusion in the Malverns Complex. (Photo: T.C. Pharaoh.)

dyke locally has a chilled margin against overlying granite, but has a tectonic contact with the underlying metadiorite (Penn and French, 1971, pp. 32, 33; Bullard, 1989, pp. 28, 29).

Earnslaw Quarry (SO 771 445)

Earnslaw Quarry (Figure 4.3) provides exposures illustrating well the heterogeneous nature of the Malverns Complex. Microdiorite dykes intrude diorite and younger, well-jointed, pink granite. The quarry is unique in containing the only known occurrence of a potassium-rich trachyte body within the complex (Thorpe, 1971; Barclay *et al.*, 1997). This outcrops on an E–W step across the southern part of the quarry, the base of the step forming the southern shoreline of the lake. The trachyte appears to be confined to the western part of the step, and is perhaps truncated by a NNE fault running parallel to the trend of the quarry. It strikes at about 300°, dips 75 to 80° to the north-east, and may be Caledonian (*c.* 400 Ma) in age (Beckinsale *et al.*, 1981). A fault zone immediately to the north of the body separates diorite to the north from coarse-grained, pink granite to the south.

Thorpe (1971) gave a detailed description of the trachyte. It is a fine-grained, dull grey rock with scattered spots and veins of carbonate. It is composed of a mass of monoclinic potassium feldspar laths showing Carlsbad twinning and alteration to white micaceous minerals. The laths show trachytic alignment around hexagonal, rectangular and anhedral carbonate (mainly) pseudomorphs; chlorite, iron-titanium oxides, a colourless fibrous mineral (possibly chlorite) and quartz also occur. The hexagonal form of some of the crystals may suggest the former presence of nepheline, although the elongation seen in some outlines is consistent with an amphibole. The chilled margin of the intrusion comprises an extremely fine-grained, cryptocrystalline feldspathic base with some angular quartz and microcline xenocrysts and autobrecciated trachyte fragments. Pegmatite-like carbonate pockets occur in the centre of the intrusion and in the highly deformed margin of the granite, which is extensively veined with carbonate.

In the south-eastern corner of the quarry, a

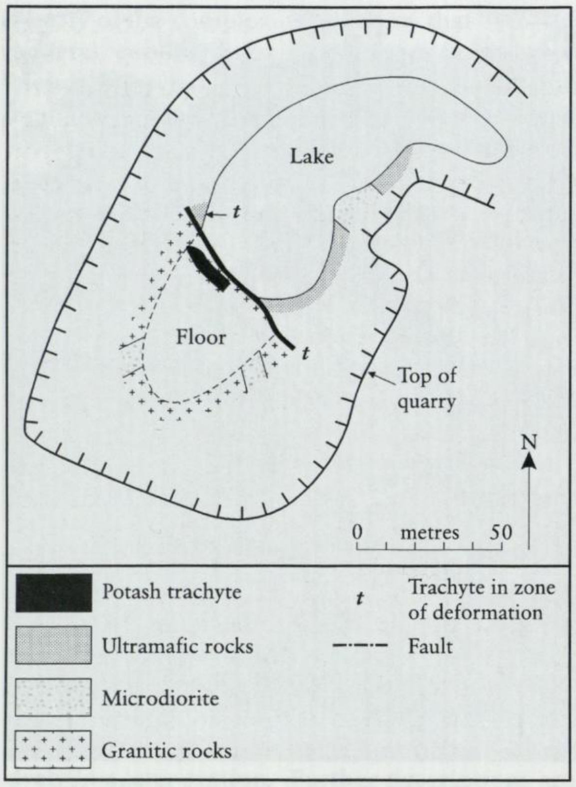

Figure 4.3 Geological sketch map of Earnslaw Quarry (after Thorpe, 1971).

microdiorite sheet at least 7 m thick intrudes coarse-grained, pink and green granite. The contact strikes at 150° and dips 60 to 70° to the north-east.

Lower Tollgate Quarry (SO 770 442–7697 4410)

This is the most northerly of the Tollgate quarries and comprises two sub-quarries (SO 770 442; 7697 4410). The main face of the northerly quarry, at the former grid reference, is now largely obscured, but there are small crags of pink granite with some green dioritic xenoliths on the eastern side of the car park. The southerly quarry exposes mainly granites, but a wide range of fine- to coarse-grained rock types, including diorite, amphibolite and hornblende-biotite rocks, has also been recorded. Brammall (1940) described a hornblende pyroxenite in a neck between two parts of the quarry. A pegmatite outcropping by the roadside between the two quarries consists of biotite 'books', hornblende, potassium feldspar and orthoclase. It is the coarsest pegmatite known in the Malverns Complex. A 5 m-thick microdiorite sheet at the south end of the southerly quarry strikes at about 290°.

Upper Tollgate Quarry (SO 7695 4395)

This quarry (also named Upper Wyche Quarry) is the most southerly of the Tollgate quarries. It exposes mainly pink, massive, foliated microcline granite. The granite is locally mylonitized, with E–W elongation of quartz and biotite. A prominent (? Variscan) shear plane dips about 45° south in the main face and there are prominent steep, east-dipping joints. Small amounts of garnet are recorded and a microdiorite dyke is present in the eastern wall (Lambert and Holland, 1971, pp. 229, 230; Penn and French, 1971, pp. 29, 30).

Wyche Cutting (SO 7688 4370–7696 4372)

The Wyche cutting on the B4218 (Figure 4.4) is excavated along a shear zone between schistose diorites to the south and more massive granites to the north (Brammall, 1940; Penn and French, 1971; Thorpe, 1987). Late, brittle shearing appears to have been superimposed on early ductile shearing. Mylonites occur along the shear zone, and the cutting provides one of the few, easily accessible, good exposures of such rocks in England. It is also the only locality at which pseudotachylites have been recorded (Thorpe, 1987).

Behind the public toilets at the western end of the cutting, mylonitized granite shows heterogeneous strain effects in which high-strain zones with more intense mylonitic foliation separate boudins of less deformed granite and pegmatite. The mylonites have a low-angle to steeply south-dipping foliation and sub-horizontal lineation on the foliation surfaces. Eastwards, the strike swings to E–W and the dip steepens, reaching vertical in the centre of the cutting. Farther east, the strike swings to ESE with lessening dip. The foliation around this arcuate strike dips towards a point on the northern slope of Perseverance Hill, south of the cutting. The structure was

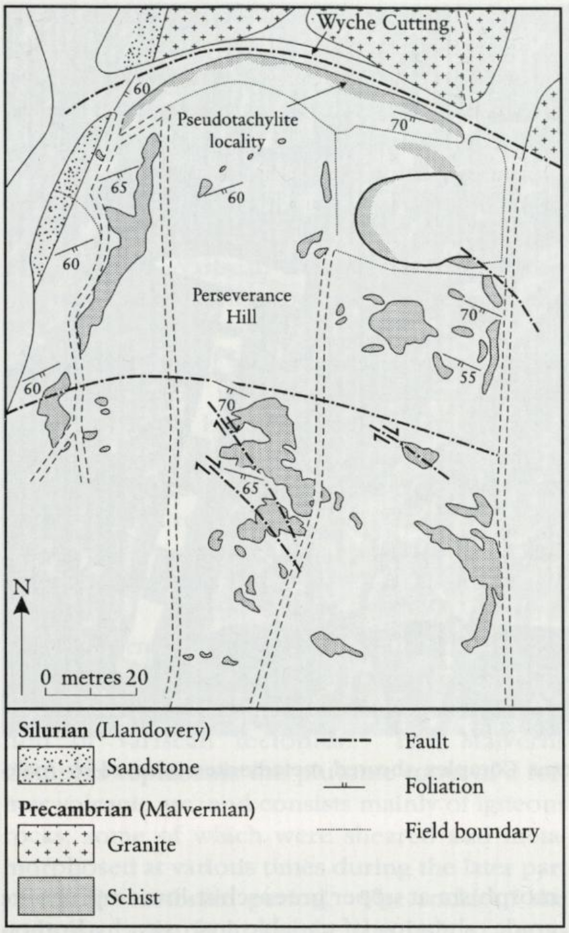

Figure 4.4 Geological map of the Wyche cutting, after Thorpe (1987) and Brammall (1940).

attributed by Brammall (1940) to NNW-directed thrusting, resulting in the schistose diorites being deformed against the buttress of the more competent granite block, and the shear fabrics confirm this interpretation. The granite is also locally sheared, particularly along a gully occupied by a highly sheared dolerite dyke (Penn and French, 1971).

The pseudotachylite occurs in dark veins within intensely sheared, heterogeneous rocks, including tonalite relicts and more competent granite, on the south-eastern side of the cutting (SO 7694 4370). Thorpe (1987) describes it in detail. The veins range from millimetre-size up to 20 mm and are prominent in the more massive granite. One 10 mm-thick vein intruded into a sheared granite has contact-parallel flow-banding defined by variation in grain size and xenocryst content. The matrix is uniformly fine-grained and comprises cryptocrystalline acicular and/or platey phyllosilicates in random orientation, with minor quartz, white mica and Fe-Ti oxide. The flow banding is defined by bands of anhedral quartz crystals. The matrix contains angular xenocrysts and microxenoliths of the host rock, and both host rock and vein are cut by fractures with hydrated and non-hydrated Fe-Ti oxides (± chlorite) and which are associated with reddening of the surrounding vein.

Gullet Quarry (SO 762 382)

Although many of the faces in this large quarry are inaccessible, there are some accessible sections in the Malverns Complex. Also, high up at the west end of the quarry is the famous exposure of the pre-Llandovery unconformity, with a basal conglomerate containing pebbles and cobbles of Malverns Complex resting on an irregular Precambrian rock surface (Brooks, 1970; Reading and Poole, 1961). A prominent NE-trending foliation, which dips steeply to the south-east, is the most obvious structure; all rocks are intensely sheared, giving a range of mylonitic and phyllonitic fabrics. A microdiorite sheet from this quarry has been chemically analysed, and shown to belong to the late-stage Precambrian intrusive phase mentioned earlier (Barclay *et al.*, 1997).

The quarry was worked on three levels, the lowest now being flooded. On entering the quarry on the second level, a ramp on the north-eastern side leading down to the water affords good exposures of the lithologies present. On the south side of the ramp, immediately underneath the car park, chloritic sheared rocks are exposed. On the north side of the ramp, pink granitic veins and sheets intrude the host greenish grey, fine-grained dioritic rocks (Figure 4.5). The veins range from centimetre size up to 2–3 m thick and pre-date the shearing of the protolith, imparting a gneissose banded appearance and mylonitic fabric to the rocks, with stretching and local boudinaging of the veins. Low-angle, SE-dipping faults of probable Variscan age cut the exposures. At the top of the ramp, an intensely sheared zone of green, chloritic rocks and red, haematitic rocks strikes at about 354°. The top level of the quarry is less accessible than the second level, but a faulted, sub-horizontal dyke can be seen in the eastern face in favourable light conditions (B. Moorlock, pers. comm. 1998). The pre-Llandovery unconformity is mostly inaccessible, but can be exam-

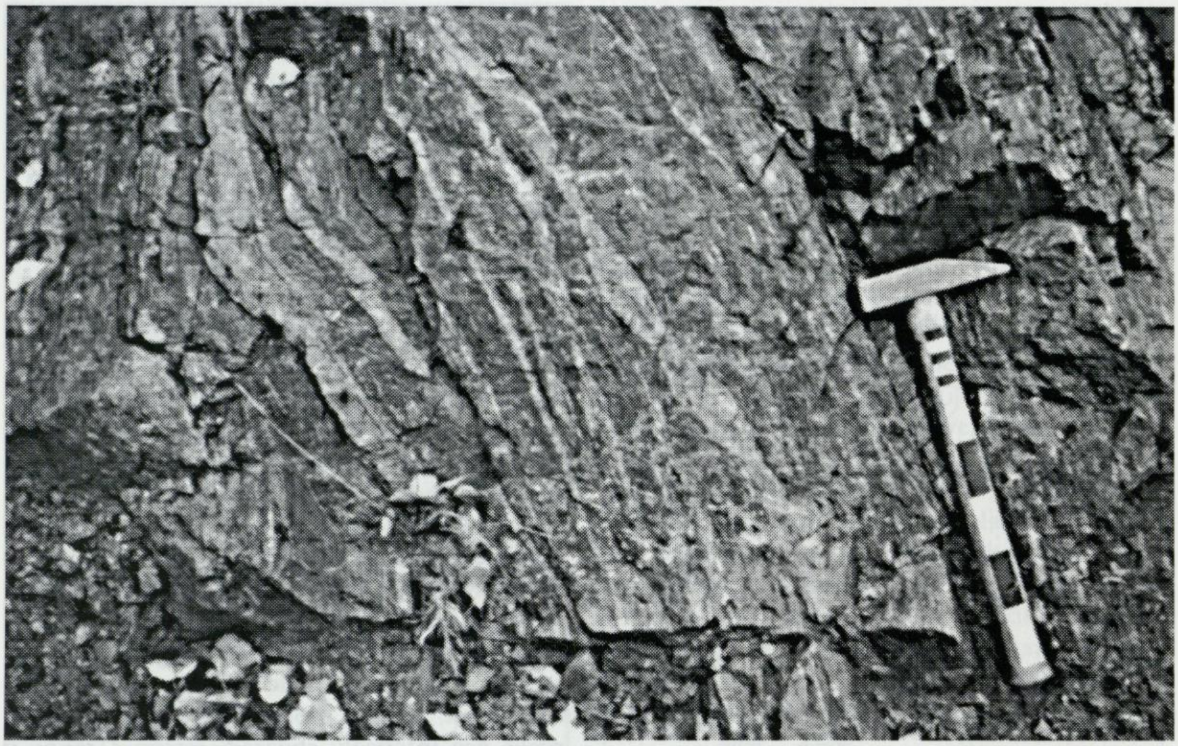

Figure 4.5 Exposure in Gullet Quarry, showing Malverns Complex sheared metadiorites injected by (pale-toned) granitic veins. (Photo: T.C. Pharaoh.)

ined in the highest, north-western part of the quarry.

The massive, mafic rocks in this quarry were termed epidiorites by Lambert and Holland (1971). They possess a distinct metamorphic texture and consist of about 50 per cent green hornblende, with partly sericitized oligoclase, subsidiary chlorite, epidote, quartz and opaque oxide. It has been suggested that some of these well-foliated rocks are of metasedimentary origin (Bullard, 1989).

Interpretation

The Malverns Complex is a deformed and metamorphosed, multiphase Precambrian igneous association forming part of the Wrekin Terrane (Figure 1.1). The calc-alkaline geochemistry of these rocks, discussed above, supports an interpretation of the complex as the magmatic root of a volcanic arc above a subduction zone (Barclay *et al.*, 1997; Thorpe, 1972b, 1974; Thorpe *et al.*, 1984). The variety of igneous relationships indicates that the complex underwent an episodic late Precambrian tectonothermal history. This involved two periods of granite intrusion, metamorphism at upper greenschist-low amphibolite grade, shearing of variable intensity, hydrothermal alteration, the intrusion of microdiorite dykes and sheets, and finally pegmatite and felsic vein intrusion (Bullard, 1975). The shear deformation, which converted many of the igneous lithologies to schistose, gneissose and mylonitic rocks, is particularly intense in the south of the Malverns. Together with thermal rejuvenation of the complex, manifested by the cross-cutting pegmatites, it represents a complicated post-emplacement history that occurred between 650 and 600 Ma. The geochemical differences between the early igneous components of the Malverns Complex and the younger microdiorite sheets reflect a further major change in this part of the Wrekin Terrane, involving the late generation of magmas with compositions comparable to typical within-plate basalts. A subsequent phase of compression resulted in thrust-faulting, which juxtaposed the complex against younger Precambrian volcanic rocks of the Warren House Formation, these forming Tinker's Hill, Broad Down and Hangman's Hill.

Thorpe (1987) concluded that the features shown by the pseudotachylite veins in the Wyche Cutting are consistent with frictional melting in an episode of high strain during stick-slip or seismic fault motion at relatively shallow depth (possibly less than 4–5 km). This resulted in the rapid injection of the melt into the surrounding mylonitic granite, followed by devitrification and/or hydrothermal alteration and further deformation. Variscan transpression produced the major faulted monoclinal structure of the Malvern Hills that is seen today.

The trachyte of possible Caledonian age in Earnslaw Quarry is unusual in being alkaline (with 13% K_2O), but geochemical data (Thorpe, 1971; Barclay *et al.*, 1997) indicate that it formed by melting of biotite-rich Malverns Complex host rock.

Conclusions

The Malvern Hills form one of the largest and best-exposed outcrops of Precambrian rocks in England, and provide a spectacular demonstration of Variscan tectonics. The Malverns Complex represents the plutonic roots of a former volcanic arc, and consists mainly of igneous rocks, some of which were sheared and metamorphosed at various times during the later part of the Precambrian period. The rocks of the complex range from granite through to 'intermediate' varieties such as diorites and metadiorites, into mafic types represented by amphibolites. There are also younger suites, consisting of pegmatite and microdiorites. A tonalite has been dated at 677 ± 2 Ma, making the complex possibly the second oldest component in the Avalonian Composite Terrane of southern Britain, after the Stanner–Hanter Complex.

Several of the quarries may be highlighted as having unique features, adding to their scientific and educational importance. Dingle Quarry provides a safe, easily accessible, 'hands-on' locality at which to examine the age relationships between some of the igneous components of Malverns Complex. Earnslaw Quarry contains the only known occurrence of a potassium-rich trachyte body within the complex. The Tollgate quarries provide good exposures, with the coarsest-textured pegmatite recorded in the Malverns being present in Lower Tollgate Quarry. The Wyche Cutting is the only locality to reveal pseudotachylite veins, formed by the injection of melted rock during frictional heating in a shear zone. It is a good locality at which to examine mylonitic fabrics, also produced by intense shear deformation. Gullet Quarry amply demonstrates the effects of retrogressive shearing on the plutonic rocks, and is also the only locality where the unconformity between the Malverns Complex and the overlying Llandovery Series (early Silurian) is exposed.

LOCALITIES IN THE WARREN HOUSE FORMATION (BROAD DOWN) (SO 395 765)

Introduction

Broad Down lies on the Malverns ridge, 4 km from its southern end (Figure 4.1). Along with Tinker's Hill to the north and Hangman's Hill to the south, it is underlain by volcanic rocks of the Warren House Formation. This comprises spilitic basalt lavas, locally displaying pillow structure, altered intermediate lavas (keratophyres), altered rhyolitic lavas and felsic pyroclastic rocks. According to French and Winchester (pers. comm. to Lambert and Holland, 1971), the formation occurs in an easterly plunging syncline with mafic rocks to the west overlain by felsic rocks to the east. Excavations at the reservoir (SO 765 399) at the time of its construction (Acland, 1898; Green, 1895) revealed that the situation is more complex, with a sequence of interbedded basalts, rhyolites and tuffs and an easterly dip ranging from 45° to near vertical (Worssam *et al.*, 1989).

Penn and French (1971), Worssam *et al.* (1989), Bullard (1989) and Barclay *et al.* (1997) give details of this area, and the petrography of the various rock types was described by Platt (1933). The preservation of pillow structures and other primary textures, and the weakness of the greenschist facies foliation contrasts strongly with the much more intense deformation and metamorphism of the Malverns Complex. The contact between the two units is tectonic, post-dating eruption of the Warren House lavas, and was attributed by Barclay *et al.* (1997) to late Avalonian tectonism at the end of the Proterozoic, possibly the same event during which the Longmyndian Supergroup was folded (see Chapter 5, Introduction).

Pharaoh *et al.* (1987b) studied the trace element geochemistry of the lavas. They demonstrated a strong enrichment in large ion lithophile (LIL) elements such as Ba, and Th, whereas the content of High Field Strength (HFS) elements such as Ti, Y and Zr lies close to or just below that of mid-ocean-ridge basalts (MORB). The geochemical characteristics are most similar to those of basalts from primitive volcanic arc and oceanic marginal basin complexes in the western Pacific (Saunders and Tarney, 1984), and to Pan-African ophiolites (proposed marginal basin crust) of the Arabian Shield (e.g. Klemenic, 1987). The geochemical patterns of the Warren House intermediate and felsic lavas parallel those of the basaltic rocks, and suggest that they may be derived from the latter by differentiation. The Warren House rocks do not compare chemically with the Malverns Complex, nor with the extrusive lithologies of the Uriconian Group (Chapter 5) elsewhere in the Wrekin Terrane. Pharaoh *et al.* (1987b) concluded that they were probably erupted in an oceanic marginal basin (Figure 1.4), and were subsequently preserved as a tectonic sliver along a late Precambrian suture (the Malvern line) between the Wrekin and Charnwood terranes (Barclay *et al.*, 1997, and Figure 1.1). On the other hand, Strachan *et al.* (1996) argued that there was no evidence from ductile fabric orientations in the Malverns Complex that the Malvern line acted as a major terrane boundary.

The Warren House lavas were dated using the U-Pb isotope system (Tucker and Pharaoh, 1991). Zircon fractions from a crystal-lithic tuff of rhyolitic composition on Broad Down (SO 7655 3960) yielded an eruption age of 566 ± 2 Ma, identical to that obtained for the Uriconian Group of Shropshire (Tucker and Pharaoh, 1991); however, as previously discussed, the two are not chemically identical.

Description

Clutter's Cave (SO 7628 3935)

This small, man-made cave is also known as Giant's Cave. The rocks are closely jointed and fractured, grey-weathering, purple-blue, spilitic (sodium-rich) basalt. (Bullard, 1989; Penn and French, 1971; Worssam *et al.*, 1989). Bun-size and loaf-size pillow structures are visible at the cave entrance (Figure 4.6) and larger ones 0.8 m across are present above and to the north of the cave. The lavas are vesicular locally, with green epidote and altered glass filling the vesicles. Joints are filled with haematite, calcite and epi-

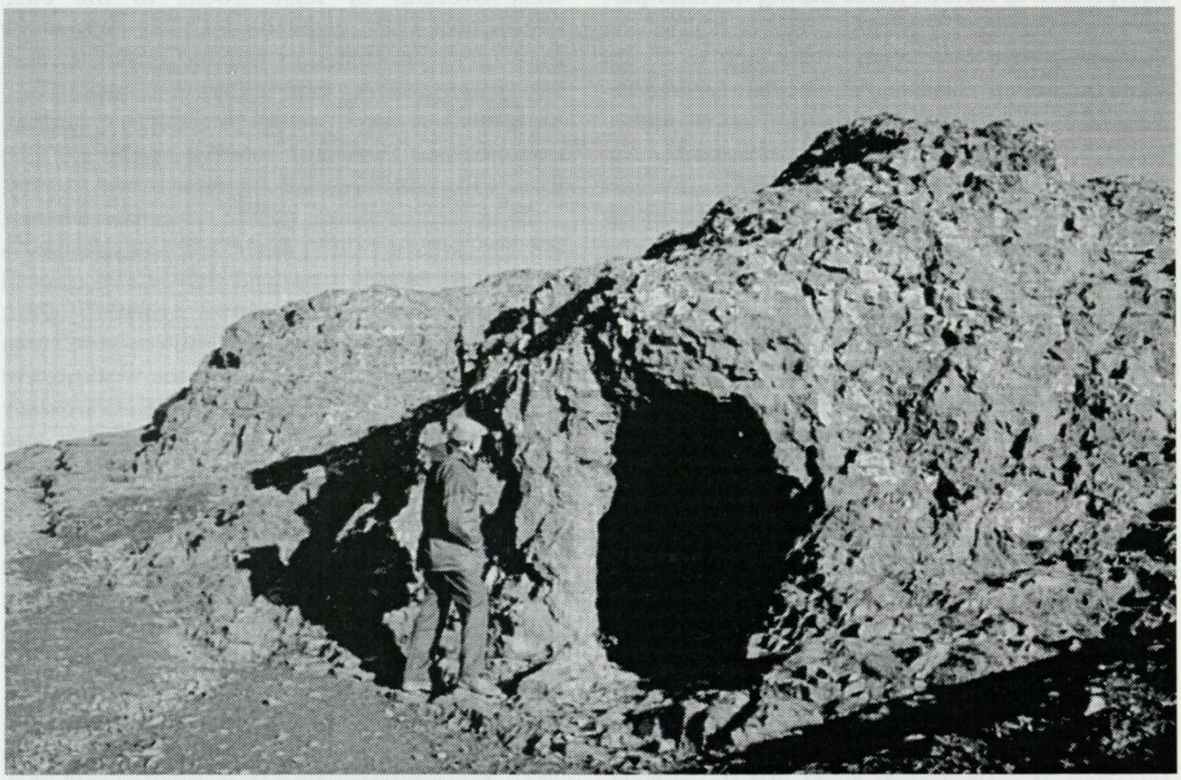

Figure 4.6 Exposure at Clutter's Cave, Broad Down, showing massive spilitic lavas of the Warren House Formation with pillow structures (e.g. in front of observer). (Photo: T.C. Pharaoh.)

dote. These secondary minerals are typical alteration products of tholeiitic lavas erupted under the sea. A few metres north of the cave, a small gully is eroded down the course of a narrow (0.2–0.3 m) breccia layer striking at about 40 to 45°. This may be a tectonically modified breccia between two lava flows. Immediately south of the cave, planes striking at 60° and dipping 60° north-west may be depositional surfaces of the lava sequence.

Reservoir Quarry (SO 766 397)

Platt (1933), Penn and French (1971) and Bullard (1989) gave descriptions of this quarry. It exposes pink and blue massive, uniform crystal-lithic tuffs that are mainly non-welded, but with some welding evident. Sheared microdiorite apparently intrudes the tuffs, although there appears to be rather lower proportions of doleritic rock than indicated by Bullard (1989). The quarry is divided into two parts separated by a NE-trending ridge. The freshest rocks exposed at the lowest level of the north wall of the northern sector are felsic, rhyolitic fragmental tuffs with rounded quartz xenocrysts. Fragmental rocks of intermediate composition are present in both sectors. In the southern sector, for example, a 0.3 m-thick pale pink to yellow-brown felsic tuff is overlain by finer-grained, greyish purple tuff of more intermediate composition, indicating the presence of compositional and grain size banding. The junction between the tuffs dips about 20° to the south-east. The intermediate tuffs are veined with epidote and the top of the upper face in the southern sector is strongly tectonized along east-dipping (? Variscan) shear planes.

Interpretation

The eruption age of 566 ± 2 Ma, determined on a tuff from Broad Down, indicates that the Warren House Formation was formed late in the history of the Precambrian Avalonian arc system. Its age is identical to that obtained for the Uriconian Group of Shropshire (Tucker and Pharaoh, 1991), and indeed the formation was correlated with the Uriconian lavas, described in Chapter 5, on lithological criteria (Callaway, 1880; Earp and Hains, 1971). Geochemical contrasts between the two suites discussed earlier suggest, however, that the Warren House Formation formed in an intra-oceanic marginal basin setting, whereas the Uriconian Group is representative of eruption within an ensialic marginal basin (Figure 1.4). These findings indicate that the Wrekin Terrane was affected by variable degrees of crustal extension during the main phase of magmatism. Thorpe (1972a, 1974) concluded that the Warren House basalts were originally tholeiitic lavas of possible ocean-floor affinity, although the presence of felsic tuffs, some of which could be the deposits of pyroclastic ash flows, or have been interpreted as ignimbrites (Bullard, 1989), causes some problems with such an origin.

The relationship between the Malverns Complex and the Warren House Formation has generated much discussion. That the latter is about 100 Ma younger is confirmed by recent age dating (Tucker and Pharaoh, 1991). However, several authors have proposed an unconformable relationship, whilst others have proposed a faulted contact. Worssam *et al.* (1989) concluded that the contact between the two units is a tectonic surface, formed after the eruption of the Warren House lavas. Barclay *et al.* (1997) attributed this to deformation that resulted from late Avalonian terrane amalgamation, in very latest Precambrian time; possibly this was the same event that folded the Longmyndian Supergroup of Shropshire (Chapter 5).

Conclusions

Broad Down provides excellent exposures of the late Precambrian volcanic and volcaniclastic rocks of the Warren House Formation. The diverse succession includes spilitized, basic pillow lavas, altered intermediate lavas (keratophyres) and rhyolitic, welded and non-welded tuffs, some of which may represent pyroclastic ash flows and ignimbrites. Radiometric analysis has given an eruption age of 566 ± 2 Ma, and although this is identical to the age of the Uriconian Group of Shropshire (Tucker and Pharaoh, 1991) these two major rock suites are dissimilar in their geochemistry. The Warren House Formation was probably erupted in an oceanic marginal basin setting, and then brought into tectonic contact with the Malverns Complex much later in the Precambrian.