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]; [SO 771 469]; [SO 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 micro-folds (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 159813 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 microdior-ite 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 northwestern 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 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 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]–[SO 7697 4410]

This is the most northerly of the Tollgate quarries and comprises two sub-quarries [SO 770 442]; [SO 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 Malvern 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]–[SO 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 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 northeastern 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, chlo-ritic 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 examined 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, meta morphism 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 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 transgression produced the major faulted monoclinal structure of the Malvern Hills that is seen today.

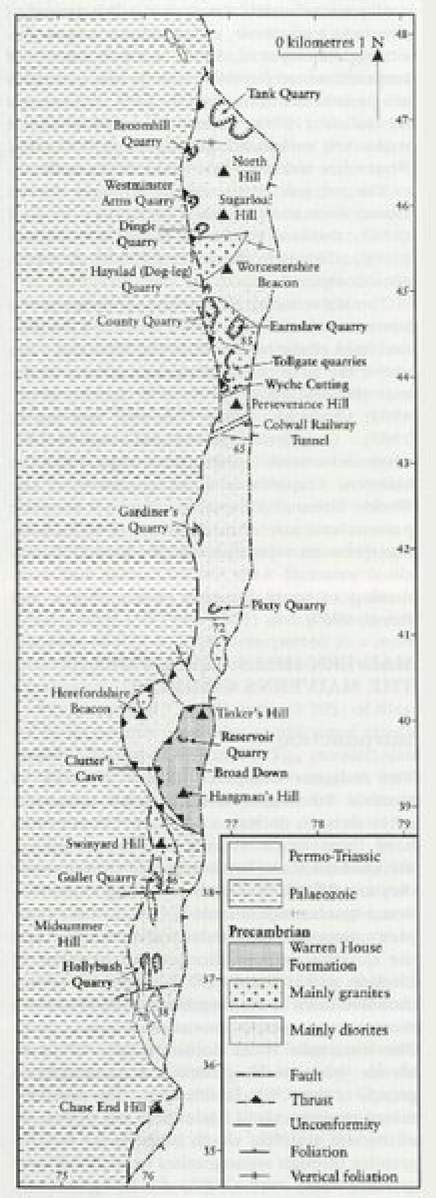
The trachyte of possible Caledonian age in Earnslaw Quarry is unusual in being alkaline (with 13% K_20), but geochemical data (Thorpe, 1971; Barclay *et al.,* 1997) indicate that it formed by melting of biotite-rich Malverns Complex host rock.

Conclusions

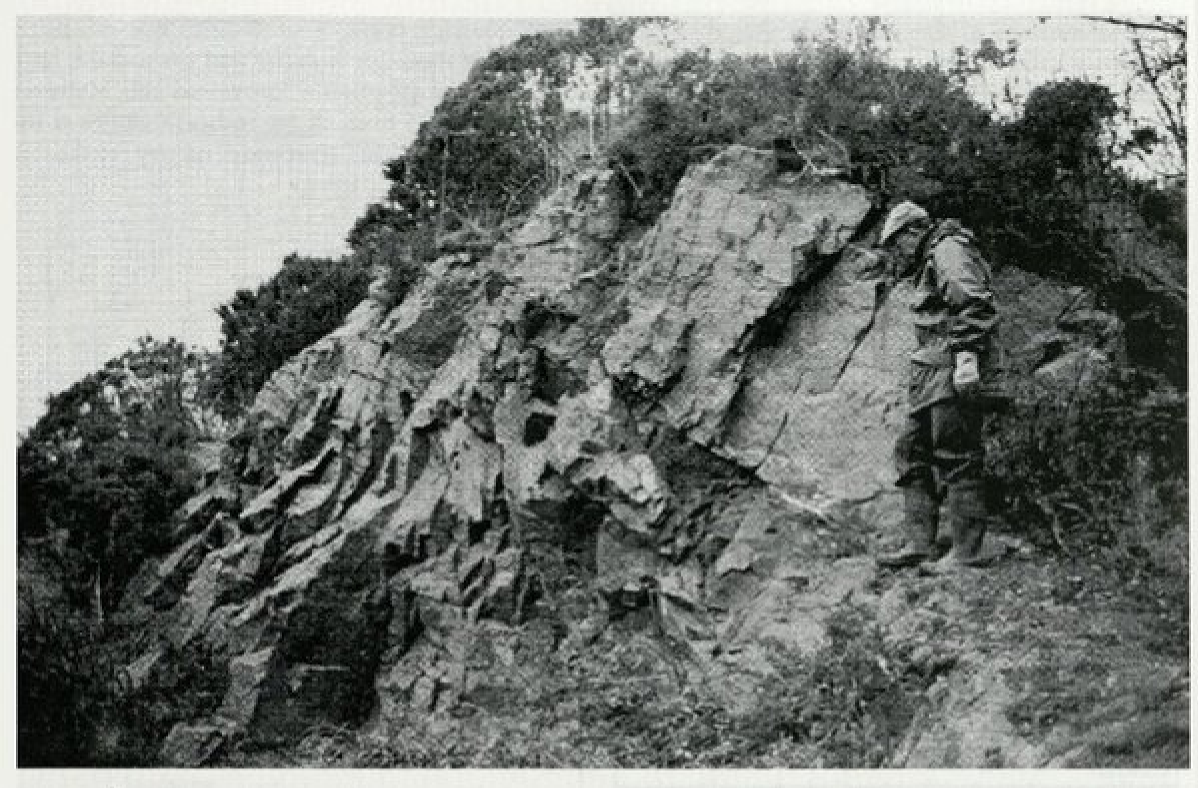
The Malvern Hills form one of the largest and best-exposed outcrops of Precambrian rocks in England, and provide a spectacular demonstration of Variscan tectonics. The Malverns Complex represents the plutonic roots of a former volcanic arc, and consists mainly of igneous rocks, some of which were sheared 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.

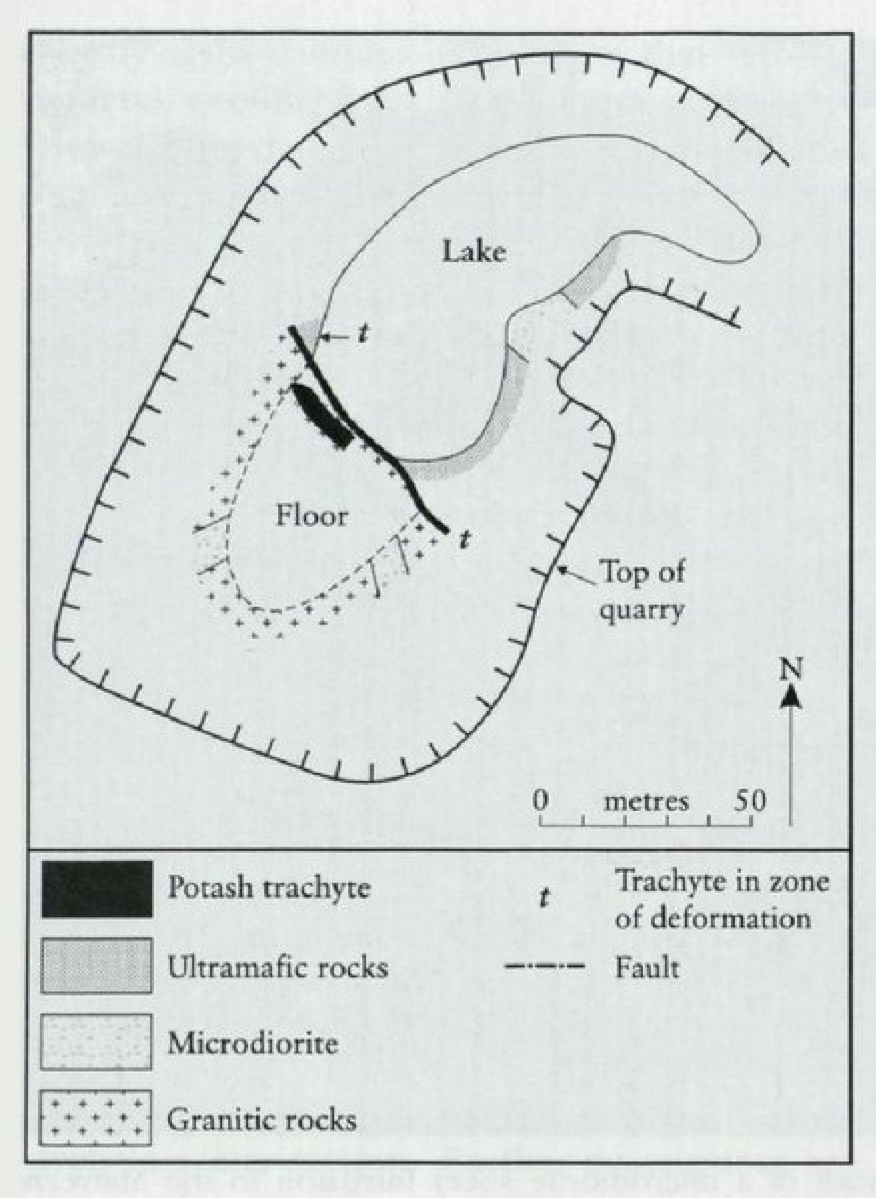
References



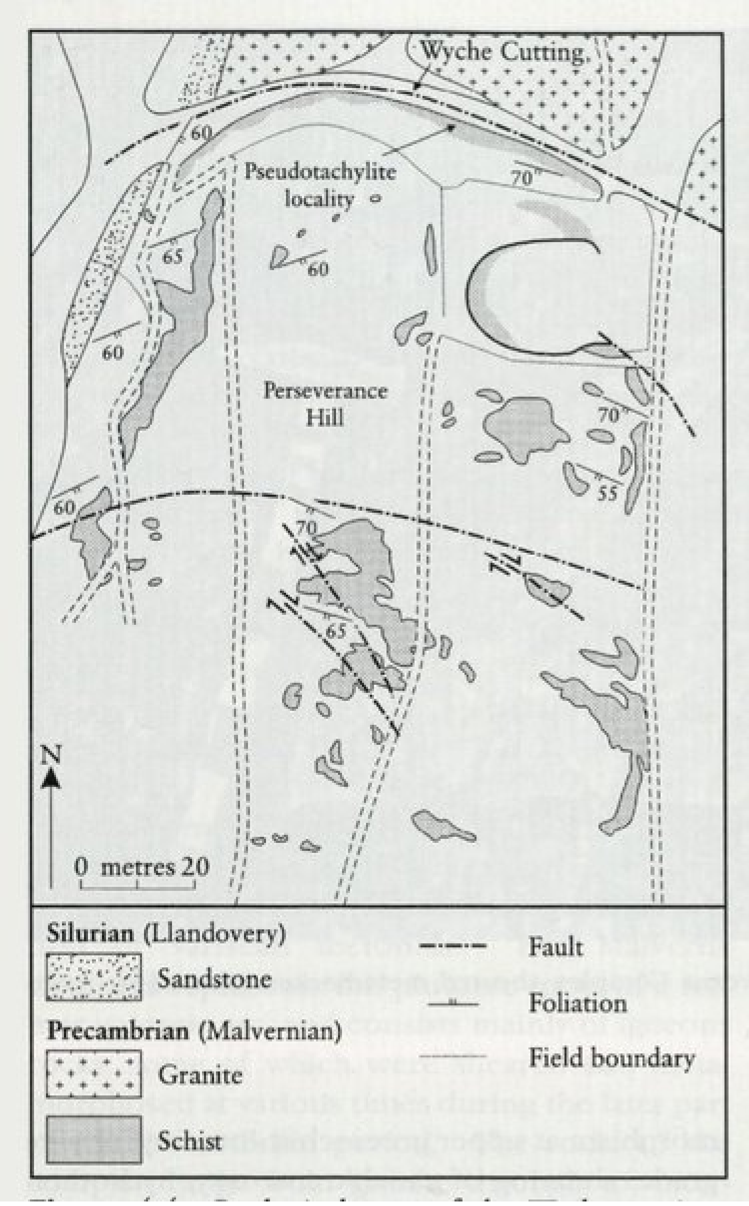
(Figure 4.1) Geological map of the Malvern Hills site, with main localities shown by bold lettering. Note that locally the granites and diorites are strongly foliated with schistose to gneissose fabrics developed. The map includes structural information from R. A. Strachan (pers. comm.) and Bullard (1975).



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

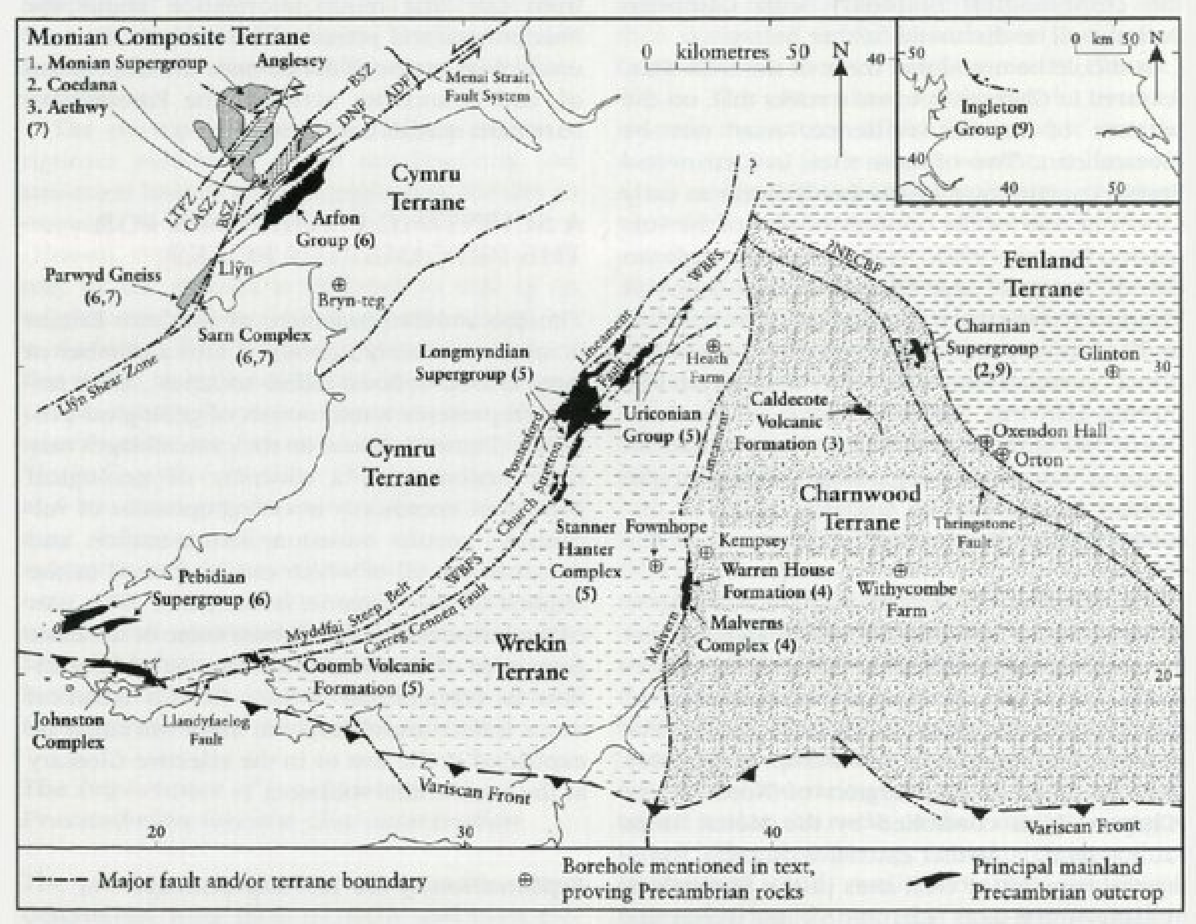


(Figure 4.3) Geological sketch map of Earnslaw Quarry (after Thorpe, 1971).



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

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



(Figure 1.1) Sketch map showing the distribution of Precambrian outcrop, and boreholes proving Precambrian rocks, in southern Britain. Note that the outcrops are labelled with the names of the principal geological units, followed by numbers (in brackets) of the chapters for the relevant GCR sites. Terrane boundaries are slightly modified after British Geological Survey (1996); Myddfai Steep Belt after Woodcock (1984a); Monian Composite Terrane after Gibbons and Horák (1990). Key: ADF, Aber-Dinlle Fault; BSZ, Berw Shear Zone; CASZ, Central Anglesey Shear Zone; DNF, Dinorwic Fault; LTFZ, Llyn Traffwll Fault Zone; ?NECBF, postulated NE Charnwood Boundary Fault. The boundary of the Midlands Microcraton basement domain is outlined by the NECBF and Pontesford-Myddfai lineament systems; WBFS, Welsh Borderland Fault System.