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GUIDE TO THE GEOLOGY OF MOUNT St. BERNARD, CHARNWOOD LODGE, WARREN HILLS AND BARDON HILL, CHARNWOOD FOREST

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Including a provisional itinerary and details of localities

In Bardon Hill Quarry, view looking north-east of the faces excavated below Bardon Hill summit, showing the deeply incised unconformity surface separating Precambrian basement from overlying Triassic 'red-bed' strata of the Mercia Mudstone Group. Photo was taken in 1999.

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Suggested Itinerary

For general map of locations, see Figure 1.

Meet up at Mount St Bernard Abbey (SK 4583 1610). Then proceed to Charnwood Lodge and Warren Hills, returning for lunch.

Afternoon: drive to footpath up Bardon Hill. Path starts from the Agar Nook estate (eastern outskirts of Coalville), off Roman Crescent at SK 4579 1410

Contents

[1] NB: 1) During midsummer the traverse between localities C and D may be affected by dense bracken growth. 2) A permit from the Leicestershire and Rutland Wildlife Trust is required in order to enter the land between localities B and D.

1. THE SCENERY OF CHARNWOOD LODGE AND WARREN HILLS

The excursion will take in areas (Figure 1) that exemplify the contrasting scenery of Charnwood Forest, with its craggy knolls separated by featureless tracts or smooth-sided valleys. This landscape is controlled by geology, and is caused by the influence of erosion on rocks with very different physical properties. The Precambrian rocks, which are the subject of this excursion, are extremely resistant to erosion. They represent the tips of an ancient, rugged hill range that is only now beginning to protrude through a covering of younger and much softer Triassic strata, the latter in turn blanketed by Quaternary deposits. Past workers have viewed Charnwood Forest's topography as being a 'fossil' or an 'exhumed' landscape, because a mountainous topography on the Precambrian rocks was already in existence before being buried by younger strata in Triassic times, about 240 million years ago. This ancient landscape is dramatically revealed in the walls of Bardon Hill Quarry, which will be viewed from the summit of the hill. It is only now emerging because the covering of Triassic strata (and also Quaternary deposits) is being preferentially removed by modern-day erosion (see inset to Figure 2).

2. INTRODUCTION TO CHARNWOOD FOREST'S GEOLOGY

Charnwood Forest is important geologically because it is one of the few parts of England where there are exposures of Precambrian rocks, which are more usually buried beneath kilometres of younger strata. These 'hard rock' outcrops, as well as furnishing local supplies of building material, have also attracted much scientific interest over the centuries, and Watts (1947) charts a number of publications extending back to 1790.

Between 1833 and 1837 the early geologists had worked out the **structure** of the Precambrian rocks. They used measurements of the inclination, or dip, of bedding to deduce that these rocks were exposed within the core of a major anticline (the Charnian anticline of Figure 2), which represents an up-folding of the strata. They also worked out the volcanic origin of these rocks, even though the study of volcanology, and igneous rocks in general, was then in its infancy. The rocks visited today are amongst the most important in Charnwood Forest because they give clues to the types of volcanic eruptions that took place. To interpret their origins, it is necessary to employ the concept of **uniformitarianism.** This states that processes we can observe today, for example certain types of volcanic activity, must also have operated in the past and can therefore explain certain of the features found in the rocks of NW Charnwood Forest.

Many rocks in Charnwood Forest were laid down layer upon layer to produce a *stratigraphical sequence* - a succession of distinctive rock units that have been given local names by Moseley and Ford (1985). The rocks seen today are part of the **Charnian Supergroup**, which can be divided into two principal groupings, the Blackbrook Group and the younger Maplewell Group, along with their component formations and members (Figure 2). There are also volcanic complexes – areas of unstratified rocks that are believed to represent the sites of the Charnian volcanoes. The exposures seen on this excursion illustrate part of the wide variety of stratified rocks found within the **Maplewell Group**, as well as the unstratified rocks of the **Whitwick** and **Bardon Hill Volcanic Complexes**.

Age of the Charnian Supergroup

A *Precambrian* age (defined as being older than the Cambrian Period, which commenced 543 million years ago) for the Charnian rocks was hinted at as long ago as 1865. This supposition was not proved until the late 19^{th} century, however, when Charles Lapworth discovered a major unconformity between these rocks and Lower Cambrian strata at Nuneaton, about 25 km to the south-west of Charnwood Forest. The Precambrian age took on a new significance with the discovery of fossils – some of the oldest multicellular life forms seen anywhere in the World - by a schoolboy, Roger Mason, in 1957. Since then, several more fossiliferous localities have been found in Charnwood Forest (eg. Boynton and Ford, 1995). These primitive fossils form part of the Ediacaran biota, of latest Precambrian age, found in several other localities around the globe. However, much still remains to be clarified about the precise age of the Charnian Supergroup, in terms of a figure expressed in millions of years. Estimates of around 560-566 Ma have so far been suggested for part of the Maplewell Group (Compston et al., 2002), based on isotopic analyses that measure the decay of uranium to lead in radioactive minerals such as zircon. Additional isotopic determinations are currently being carried out by the BGS in order to establish a more accurate age-range for the whole of the Charnian Supergroup.

Mode of formation of the Charnian Supergroup

Clues to the origin of these rocks are to some extent contradictory. In the east, for example on Beacon Hill (Figure 2), the rocks are typically well bedded, a feature that will be seen at Warren Hills and which is typical of sedimentary rocks. On the other hand, when examined through the microscope the grain constituents – mainly consisting of volcanic rock fragments, crystals, and slivers of volcanic ash – point to a wholly volcanic origin. It is therefore accurate to say that the Charnian Supergroup is a

volcaniclastic succession. This is an ‘umbrella’ term for bracketing strata containing varying proportions of grains derived from the erosion of pre-existing volcanic successions (*epiclastic origin*), as well as material incorporated into the rock directly from volcanic eruptions (*pyroclastic origin*). Pyroclastic material may consist of non-abraded volcanic ash shards (to left of Figure 8), crystals, or angular volcanic rock-fragments. The qualifying term *tuffaceous* is commonly used for sedimentary rocks that are a mixture of epiclastic and pyroclastic grains, where the latter’s abundance is more than 25 and less than 75 per cent of the rock.

Rocks of the Maplewell Group contain the largest amounts of pyroclastic material, including ash fragments, and were therefore formed during the time of maximum volcanic activity. As Figure 2 shows, this group displays a very important **lateral change** on going north-westwards, from the stratified and predominantly medium-grained tuffaceous rocks of the Beacon Hill Formation into the thickly-developed and very coarse *volcanic breccias* of the Charnwood Lodge Volcanic Formation, which will be visited today. The occurrence of extremely coarse rocks like these is geologically significant, because it means that the source of the large fragments – the volcanoes themselves – must have lain very close to Charnwood Lodge. This suggestion is reinforced by the presence in western Charnwood Forest of rocks that could represent actual feeder zones or conduits of the volcanoes. They are typically massive (unbedded), and because they do not form part of a stratified sequence they are known as the *volcanic complexes,* of the Bardon Hill and Whitwick/Sharpley areas.

The **plate-tectonic setting** in which the Charnian rocks were formed can be partly deduced from rock chemistry, involving the analysis of silicate minerals and trace elements. These chemical studies indicate that the Charnian rocks have compositions similar to modern volcanic rocks that formed above a subduction zone (Pharaoh et al., 1987). As shown diagrammatically in Figure 3, it is likely that the magmas involved were vented to the surface within an island arc – a line of volcanoes surrounded by an ocean. Modern oceanic arcs, such as the Caribbean island arc, are by definition largely submerged and consequently the fragmental material, either eroded or ejected from the volcanoes, accumulates and is preserved on the surrounding sea floor. This is therefore the *palaeoenvironment* envisaged for the rocks of the Charnian Supergroup. Measurements of the magnetic properties of equivalent rocks at Nuneaton (Vizan et al., 2003) show that in latest Precambrian time the Charnian volcanic arc was located close to the southern Tropic, just off the margin of the Gondwana supercontinent (Figure 4a).

Evidence for the **depositional environment** of these rocks is provided by *sedimentary structures* seen in the stratified parts of the Charnian Supergroup, for example at Bradgate Park. There is a rarity of cross-bedding or current and wave-ripples, which are typical of strata deposited in shallow-water environments. Instead, sedimentary structures such as normal grading, load structures and slump-induced disruption of bedding, which can be seen at Warren Hills, indicate that deposition occurred in water deeper than about 50 m. The processes involved would have included the transport of volcanic detritus in sediment-laden submarine flows ('turbidity currents'), with earthquakes caused by tectonic or volcanic activity probably triggering individual flow-events. Finally, marine (oceanic) environments are further suggested by the types of fossil seen in Charnwood Forest.

Main deformational phase in Charnwood Forest

The last major events to affect the Charnian sequence involved the formation of the *Charnian anticline* (Figure 2), and also a highly penetrative west-north-westerly cleavage. The recrystallisation of minerals to form the micas that define the cleavage planes occurred at a depth of about 10 km and temperatures of 350^{o} C – conditions that would have prevailed within the 'roots' of a rising mountain belt.

The cleavage-forming micas have been isotopically dated (Carney et al., 2008), showing that they were not formed in Precambrian time. Instead, the cleavage formed as a result of compression during the later stages of the Caledonian orogeny, which in this region is dated at the end of the Silurian Period, about 420-416 Ma. This event was part of the end-Caledonian plate tectonic movements that closed a major ocean (Iapetus), and in the process united the landmasses of southern Britain and Scotland (Figure 4b). Just to the west of Warren Hills a major fault – the *Thringstone Fault* – defines the edge of Charnian outcrop (Figure 2). This fault was formed during the Caledonian orogeny but has moved repeatedly since, ensuring that the Charnian Precambrian rocks have at times been exposed to erosion that has stripped away the overlying, much younger strata. This active tectonic history has had important economic consequences for this region because to the west, the Carboniferous strata of the North-west Leicestershire Coalfield were preserved from erosion as they were lowered down along that side of the Thringstone Fault.

3. LOCALITY DESCRIPTIONS (A-E, Figure 1)

A. Mount St Bernard Abbey: specimens from the Whitwick Volcanic Complex (SK 4576 1621)

This Cistercian Abbey was built in the mid-19th century, close to the site of a medieval forerunner. It typifies the vernacular style of buildings in Charnwood Forest, with roof slates composed of the Swithland Formation (Brand Group), of Early Cambrian age. These slates were quarried from the Swithland and Groby areas up till the end of the 19th century, when imported Welsh slates became the main roofing material (Ramsey, 2007).

The main objective here is to examine the walls of the Abbey, where there are excellent specimens of a rock known as the **Peldar Dacite Breccia** (Carney, 2000a).These spectacular blocks of porphyritic dacite and dacite breccia are characterised by a dark grey, almost black, fine-grained matrix that encloses phenocrysts[2], many over 1 cm in length. The dark matrix indicates that this is the 'Peldar Tor' variety of porphyritic dacite, in the former terminology of Watts (1947). It does not crop out widely, but has been extracted from the nearby Whitwick Quarry where it forms a major component of the **Whitwick Volcanic Complex** (Figures 1 & 2). Specimens in the wall demonstrate the three main components of the Peldar breccia:

- Rounded or irregular-shaped fragments of dark grey to black, very fine-grained porphyritic dacite, featuring abundant large white to pink, oblong-shaped plagioclase phenocrysts and less-common, but equally large, rounded phenocrysts of green-grey, glassy quartz.
- Small, greenish grey fragments of medium-grained quartz microdiorite.
- A medium-grained 'sandy' matrix, which under the microscope consists of abundant slivers of spherulitic-textured volcanic rock, indicative of dacite glass that has devitrified.

***Interpretation**:* The Peldar Dacite Breccia is interpreted as a type of hyaloclastite breccia (hyalo = glass; clastite = made of fragments), formed by the rapid cooling and subsequent quench-induced brecciation of a phenocryst-rich magma, remnants of which now constitute the porphyritic dacite fragments. This type of brecciation is attributed to physical interactions occurring when the dacite magma was intruded at shallow depths into water-saturated sediments.

[2] In igneous rocks, phenocrysts are crystals that are significantly larger in size than the surrounding matrix crystals

Relationships attributed to this mode of emplacement are demonstrated in the nearby Whitwick Quarry, where intricate mixing has been observed at the margin of a sedimentary raft incorporated into the breccia (Carney, 2000a). Similar features have been described from strata located at the margins of magma masses called cryptodomes, and will be discussed further in the section describing the Bardon Hill locality.

A. Mount St Bernard Abbey: St Bernard Tuff Member

The crags a few metres east of the Abbey expose thin tuff beds, many showing normal grading expressed as concentrations of white plagioclase crystals at the base, fining upwards to silty, tuffaceous tops. This sequence comprises the St Bernard Tuff Member of the Charnwood Lodge Volcanic Formation (Carney, 2000a). It may represent a relatively subdued episode of volcanism in this part of the Maplewell Group, which as will be seen is dominated by bouldery volcanic breccias. The strata dip at 60^{o} to the south-west, which is also the younging direction indicated by the grading. The Charnian cleavage is roughly developed at the base of the crag below the statue; it strikes west-north-west and dips about 85^{o} northwards. Here, silicified joint faces, striking at high angles to the cleavage, show brown staining and are studded with rectangular-shaped pseudomorphs thought to represent earlier pyrite (iron sulphide) mineralisation.

The sign indicating **'Calvary'** leads on to further exposures of the St Bernard Tuff Member. Beyond the shrine marked '1836-1936', the summit is composed of massive, coarse-grained volcaniclastic sandstone. The large crystals present include feldspar and quartz, suggesting derivation from pyroclastic eruptions of the same magmas that produced the Peldar Dacite. Along this rocky footpath, many spectacular black-coloured slabs of Peldar Dacite Breccia are visible in the wall.

B. Charnwood Lodge: the ‘Bomb Rocks’ (SK 4630 1570)

This is a National Nature Reserve consisting of heathland and rocky knolls administered by the Leicestershire and Rutland Wildlife Trust. It contains within its boundaries a large SSSI, only part of which (Figure 5) will be visited on this excursion. The Reserve is the type area for the **Charnwood Lodge Volcanic Formation**, about 1000 m thick, which contains some of the most spectacular rocks in Charnwood Forest. The ‘Bomb Rocks’ locality is a remarkable exposure of very coarsely fragmental volcanic rocks. It was given this name by Watts (1947), because he thought that the large fragments seen in this rock had fallen through the air as volcanic bombs.

There are some problems with the ‘bomb’ interpretation. True volcanic bombs are formed from lava that was molten at the time they were ejected from the vent. They are identified as such on the basis of their distinctive aerodynamic shapes, many (e.g. Figure 6) being pod-like masses of lava (spindle bombs), flattened discs with cooling fractures (breadcrust bombs) or entrail-like tatters of lava (ribbon bombs). Even though volcanic bombs may break up when they hit the ground, they still show partial contorted or ribbon-like outlines indicating that they were in a semi-solidified condition when they were passing through the air. Rocks formed by the aggregation of volcanic bombs are called ‘agglomerates’, and this name has frequently been applied to the ‘Bomb Rocks’ of Charnwood Lodge.

However, the contorted, aerodynamic outlines typical of volcanic bombs are not seen here. Instead, the fragments have rectangular, diamond or tabular shapes (Figure 7) that must have been determined by original joints in solid (as opposed to molten or semi-solid) volcanic rock. These fragments are therefore more accurately called volcanic blocks and the rock as a whole is better classified as a volcanic breccia. Note that where the blocks do appear to be elongated, in end-on sections viewed towards the north-west or south-east, this is due to the deforming effect of the Charnian cleavage, the origin of which was discussed above. The blocks range from a few centimetres (lapilli-size[3]) up to 1.7 m across; on close inspection, some have highly angular corners, whereas other corners clearly show rounding and abrasion. Microscope sections of similar blocks, sampled from farther north, show that they are dissimilar to volcanic bombs in another respect – they do not have vesicular textures (vesicles are bubble-structures caused by gases exsolved within the lava as it was being erupted at or near to the surface). Yet another significant observation is that the blocks all appear to be of an identical grey andesite with small phenocrysts of plagioclase feldspar. All of these features are significant to the interpretation of these rocks, which will be discussed after the section describing Locality C.

Bedding appears to be absent within the confines of this locality, but there are marked changes in average block-size and in the proportion of matrix to block. For example, to the south-west the blocks are smaller and the coarse-grained matrix is more abundant, whereas to the east of the track blocks are present almost to the exclusion of the matrix. This indicates that the volcanic breccias of the Charnwood Lodge Formation are probably part of a thickly stratified succession.

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[3] Lapilli are volcanic fragments measuring between 2 mm and 64 mm; above this size the fragments are ‘blocks’

Because the rocks of Charnwood Lodge show little bedding, it is difficult to appreciate their **tectonic dip**. At Warren Hills, however (see below), it is apparent that the strata resting on top of these rocks dip at angles of about 40-50^{o} to the south-west. This is therefore the geological structure favoured for the Charnwood Lodge area. It is consistent with the fact that Charnwood Lodge is located on the south-western flank of the main Charnian anticlinal fold (Figure 2).

C. Charnwood Lodge: Grimley Andesite at High Tor Farm (SK 4593 1543)

Grimley Andesite is a component of the Whitwick Volcanic Complex; it is only about 70 m thick here but farther north it forms extensive masses, up to 450 m thick. In contrast to the fragmental nature of the 'Bomb Rocks', the Grimley Andesite is a homogeneous, grey, fine-grained rock, which produces smooth joint-surfaces. In overall appearance, as well as under the microscope, however, the Grimley Andesite is identical to the blocks found in the 'Bomb Rocks', and in other volcanic breccias of the Charnwood Lodge Volcanic Formation.

The importance of the 'Bomb Rocks' and Grimley Andesite localities to theories about how these rocks were formed, is now discussed.

Interpretation of the 'Bomb Rocks' and Grimley Andesite: The 'chaotic' appearance of the volcanic breccias at the Bomb Rocks (Figure 7), and evidence for fragments having collided with each other to cause partial rounding of their corners, are features suggesting an origin as debris flows. Debris flows are typically formed in high-energy sedimentary environments, for example as a result of landslides or mudflows in mountainous regions. In the context of the model that is presented below, however, these environments would have represented the steep flanks of the Charnian volcanoes.

One important observation in favour of a volcanic origin is that the blocks in the breccias are all of the same type of andesite, very similar in appearance and chemistry to the massive rocks of the Grimley Andesite. This suggests that the Grimley Andesite may be remnants of volcanic 'feeders' to the local succession, in which case it is pertinent to consider how large pieces of it came to be incorporated within these volcanic breccias. A possible explanation is that the Grimley Andesite was emplaced within the volcanic craters, not as fluid lava but as highly viscous, extrusive volcanic domes, as shown in Figure 8. Upon continual uprise and volume increase, these domes would solidify, fracture and eventually collapse, to form **ash and block pyroclastic flows**, which now, in lithified form, are represented by the Charnwood Lodge volcanic breccias (Carney, 2000a; Ambrose et al., 2007).

This is where the *principle of uniformitarianism,* discussed above, becomes important, because there is an excellent modern analogy provided by the activity of the Soufriere Hills volcano on Montserrat Island, in the Caribbean volcanic arc, which was well documented during the late 1990's. That volcano did not produce lavas. Instead the magma solidified as volcanic domes, which subsequently collapsed, sending down block-rich pyroclastic flows. These followed well-defined flow-paths (Figure 9) and eventually ran out for considerable distances (over 15 km) down the submarine flanks of the island and across the floor of the surrounding sea. The blocks that they carried would almost certainly have been modified by collisions during travel, producing rounded-off corners similar to those of many blocks seen at Charnwood Lodge.

D. WARREN HILLS (SK 4581 1526)

On the traverse from High Tor Farm to Warren Hills (bracken permitting), further exposures of Grimley Andesite and volcanic breccia of the Charnwood Lodge Formation can be examined. Warren Hills is an important locality as it exposes west-dipping strata that form a transition zone, from the coarse-grained volcaniclastic rocks of the Charnwood Lodge Formation into the overlying siltstones and sandstones of the Bradgate Formation (see also, the outcrop map of Figure 5).

On the North knoll of the ridge (Figure 10), the youngest part of the **Charnwood Lodge Volcanic Formation** is exposed. It is composed of fragmental volcanic rocks, but these are considerably less coarse in grain size compared to the volcanic breccias at the 'Bomb Rocks' locality. The succession here is dominated by massive or stratified coarse-grained *tuff and lapilli tuff*, with only minor proportions of volcanic breccia. In contrast to the 'Bomb Rocks', there are only a few scattered andesite blocks that are generally no more than several centimetres in size. A few tens of metres farther west, the Charnwood Lodge Formation has given way to massive, very coarse-grained *tuffaceous sandstone*, seen on the Middle knoll (Figure 11). This sandstone marks the base of the Bradgate Formation. It contains a persistent horizon of *sediment-raft breccia*, 3-4 m thick, carrying clasts of laminated siltstone which vary from centimetres-size slivers to contorted rafts up to 1 m long. This breccia occupies a similar stratigraphic position to, and is correlated with, the *Sliding Stone Slump Breccia*, which occurs at the junction between the Beacon Hill and Bradgate formations and has its type locality in Bradgate Park.

Up-section (ie up the 'dip' of the bedding, which is to the south-west), the basal beds of the **Bradgate Formation** constitute white-weathering, crystal-rich, medium-grained volcaniclastic sandstones, seen on the South knoll. The bases of individual sandstones are 'loaded' (forced downwards) into the underlying bed. In this sequence there are thin siltstones – probably distal turbidite beds - that *grade* upwards to mudstone-rich tops that locally show folded and disrupted lamination.

From this viewpoint, the low-lying ground to the south-west contains the North-west Leicestershire Coalfield, in part covered by Triassic strata. The Carboniferous succession is brought in along the Thringstone Fault, a reverse displacement which delimits the south-western edge of the Charnwood Forest Precambrian massif (Figure 2). The low ridge in the far distance, about 20 km to the south-west, includes the outcrop of Precambrian, Charnian-type volcaniclastic rocks at Nuneaton (Bridge et al., 1998). The mass of Bardon Hill can be seen occupying the skyline to the south. It is mainly composed of the Bardon Hill Volcanic Complex (see below), the rocks of which have been displaced westwards due to dextral (right-lateral) movement along the Abbot's Oak Fault (Figures 1 and 2).

Interpretation of Warren Hills: During the waning phase of volcanism, the strength of the Charnian eruptions weakened, as shown by the pyroclastic flows with relatively smaller fragments (compared to the 'Bomb Rocks'), forming the lapilli tuffs seen at the North knoll. Eventually, even the coarser, block and lapilli size fragments ceased to be transported to this area, resulting in the strata seen at the Middle knoll. This outcrop shows features indicating that the strata were laid down from turbidity currents, implying considerable depths of water (possibly hundreds of metres). The transition upwards through the basal part of the Bradgate Formation is marked by sediment-raft breccias. This suggests that tectonic events, causing widespread instability along the submarine slope surrounding the volcanoes, may have accompanied the decline in activity of the Charnian volcanic centres.

E. BARDON HILL (SK 4593 1321; summit)

This part of the excursion (see Figure 1) takes in the **Bardon Hill Volcanic Complex**, which includes some highly unusual rock-types which may have formed in the conduit of a Precambrian volcano. It starts at the footpath (the 'Ivanhoe Way') leading off Romans Crescent, which joins Greenhill Road linking Abbot's Oak and the Agar Nook estate (see 'Itinerary'). A short distance along this footpath there is a row of large quarried blocks. These mainly consist of grey-green andesitic breccia containing cream to pink-coloured andesite inclusions (autoliths), typical of the Bardon Breccia. There is also a block of dark grey Peldar Porphyritic Dacite, which crops out in the northern part of the quarry (Figure 1). Like the samples in the walls of Mount St Bernard Abbey, it contains large phenocrysts of white/pink plagioclase and grey-green glassy quartz in a dark grey groundmass. The last block in the row is a particularly interesting mixed rock, which has also been recognised in the Bradgate Formation outcrop in the southern part of the quarry (Carney and Pharaoh, 2000). It is a very coarse volcaniclastic sandstone in which andesitic fragments, identical to those in the Bardon Breccia, occur together with sedimentary fragments consisting of maroon mudstone or siltstone.

After traversing a steep incline through a wood the quarry perimeter fence is gained, affording expansive views of Bardon Hill summit and the quarry (Figure 12). This area has had a long and varied history of hard-rock extraction, the earliest record of such activities being that of the topographer William Burton, in 1622. The definitive account of quarrying, both here and in other parts of Charnwood Forest, is provided by McGrath (2007). It should be noted that Bardon Hill is the territory of the nationally rare 'Charnwood red' spider, and peregrine falcons may also be seen.

This locality is close to the site of the former 'Upper Siberia' quarry, where the only *in situ* occurrence of **gold mineralization** in Charnwood Forest was recorded in 1880. The location of this quarry can be found on a manuscript map (featured in McGrath, 2007) produced for the Leicester Literary and Philosophical Society Fifth Excursion, which took place on the 30th June 1906 (Keay and Gimston, 1907). The mineralization was re-discovered in 1950, at the same locality, which then was described as being 'just below the summit of Bardon Hill' (King, 1967). King noted that it occurred in association with limonite in the cavities of cavernous quartz masses, these in turn being located within a 120 m-wide shatter zone striking '50^{o} west of north', in which were developed cataclasites, phyllonites and mylonites. In a subsequent account (King, 1968), the mineralization was described as being of filigree type, in quartz veins and larger lenses (boudins?), associated with epidote, carbonates and specular hematite. Other examples of mineralization found at Bardon Hill include copper, barium, arsenic and vanadium compounds commonly occurring along the Triassic unconformity. Much of this mineralization has probably been deposited from waters percolating through the Triassic 'red-beds' of the Mercia Mudstone Group (Ince, 2007).

Continuing upwards along the fence towards the summit ridge, there are further large quarried blocks of the Bardon Breccia. All of the fragments within the breccia consist of andesite, and because the matrix is also andesitic the breccia texture is best revealed on wet surfaces. This type of breccia is known to Bardon quarrymen as the 'Good Rock'. On fresh surfaces it is pale green to greenish-grey and locally feldsparphyric; there is much epidote and chlorite alteration. The andesite fragments have sharply angular to well-rounded outlines and pale green-yellow or pink colours; when seen in the quarry some occur in clusters in which the margins of individual, highly angular fragments can be fitted together – an example of 'jigsaw' structure (Carney and Pharaoh, 2000). The matrix is coarse-grained and volcaniclastic; thin sections show it is made up of lithic (andesite) fragments and broken plagioclase crystals. In places the andesite fragments develop dark, glassy rims with spherulitic textures. It should be noted that large blocks of dark grey-green Bardon Breccia have commonly been used for ornamental purposes; for example, rows of them can be seen just inside one of the riverside entrances to Battersea Pleasure Gardens in London.

Naturally weathered exposures of these breccias will be seen for comparison along the metalled track leading past the transmitter installations, and also on the lower, south side of the summit ridge (Figure 13).

Interpretation: The Bardon Breccia may have formed when andesite magma rose upwards through wet sediments of the Bradgate Formation, seen in the quarry below, which at that time formed the sea floor surrounding the Charnian volcanic axis (Figure 8). There is evidence from the quarry that as the magmas encountered the sediments they cooled rapidly, producing glass-rimmed andesite fragments seen in the Bardon Breccia (Carney, 1999). Other exposures along the margin of the Peldar Dacite in the northern part of the quarry (Figure 1), showed intricate mixing at all scales between magma and wet sediments (Figure 14) producing a distinctive rock-type called 'peperite'. Such features typically occur in the shallow sub-surface environment, and are believed to reflect magmas that have risen to high levels, but have not quite reached the surface. Bardon Hill Quarry therefore demonstrates two important features: a) most of the Bardon Breccia and Peldar Dacite magmas must have been emplaced just below the sea floor, probably as lava domes (cryptodomes) within a carapace of wet sediment, as shown in Figure 8, and b) at times, these domes rose through the sea floor (exogenous dome stage), contributing fragments to sediments of the local Bradgate Formation succession (*above*; Carney and Pharaoh, 2000),

At the end of the ridge past the Trig point on Bardon Hill summit, the highest point in Charnwood Forest at 278 m elevation, an information board gives more details about the geology of Bardon Hill and the quarry. The stunning view from here takes in the central and western parts of the quarry, where Precambrian rocks are being extracted and crushed to make roadstone and tarmacadam. Quarrying has revealed a major unconformity, where red Triassic strata of the Mercia Mudstone Group, with thin green-grey siltstone beds, fill palaeovalleys eroded into Precambrian rocks. The relatively shallow palaeovalleys viewed from here (e.g. Figure 12) have commonly been called 'wadis'; however, in the quarry itself there are v-shaped valleys with extremely steep gradients (see Front cover picture), which must have been little more than gullies or ravines (torrent-courses) eroded into a steep, bare-rock surface on the Precambrian rocks. Owing to processes of differential compaction, the Mercia Mudstone strata sag downwards into the deeper parts of the valleys, to produce a structure known as catenary dip (Figure 12 and Front cover). Bardon Hill is a prime example of a landscape, at least 250 million years old, which was carved by winds and storms throughout the c. 50 million year duration of the arid Permian Period (between 300 and 250 million years ago). At the end of the Permian much of north-western Europe began to subside, allowing this range of rocky hills to be progressively buried by the wind-borne silt and dust of an encroaching desert. Bardon Hill is therefore one element of Charnwood Forest's 'fossil topography', which as a result of erosion over the past 40 million years is only now re-appearing from beneath its Triassic cover.

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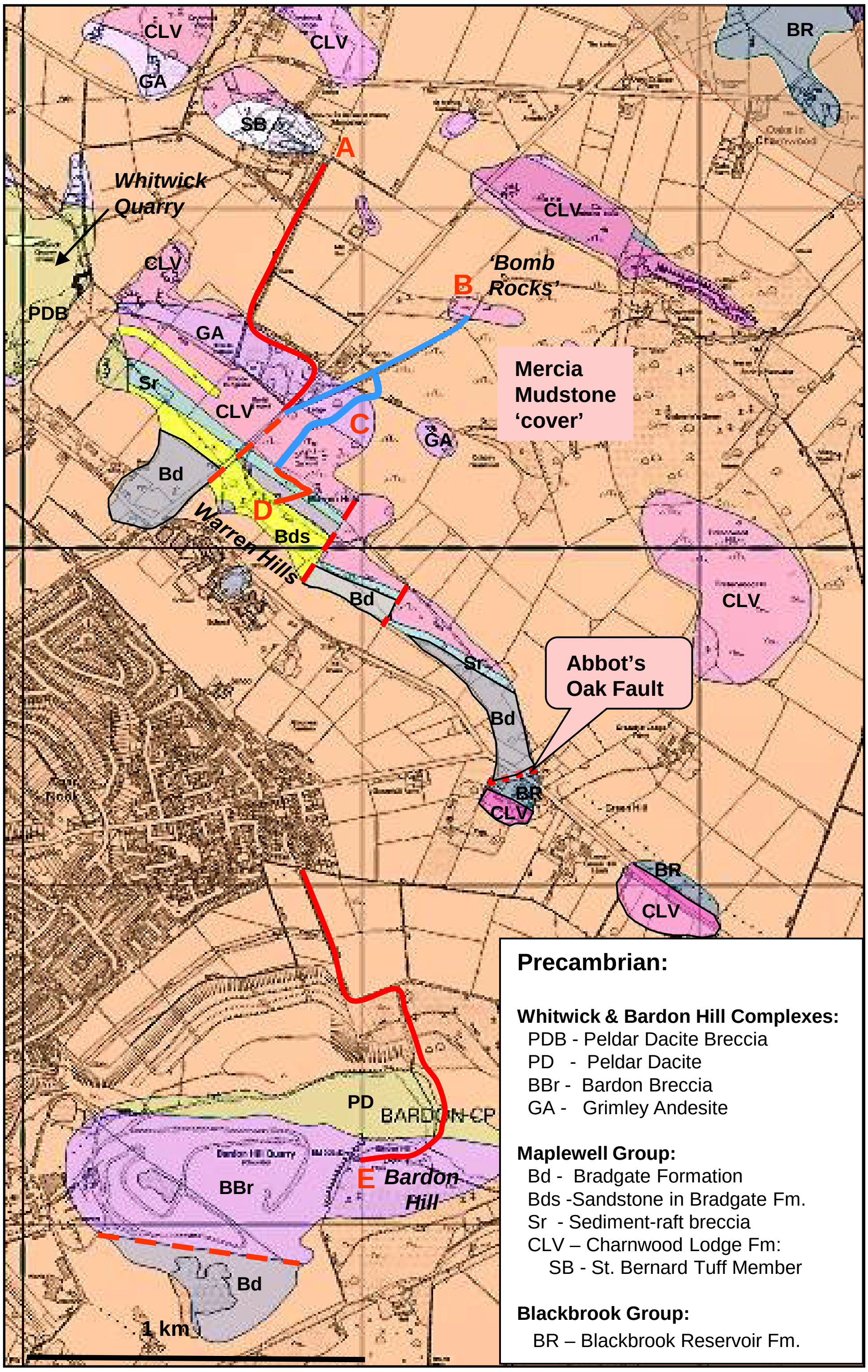


Figure 1 Geological map, showing localities A-E to be visited. Excursion routes are shown as solid lines: red = open to public, blue = requiring a permit (see footnote on p. 2). Faults are shown as red dashed lines. Quaternary deposits have been omitted. Extracted from BGS DigMap50 digital geological compilation, Sheets 141 (Loughborough) and 155 (Coalville).

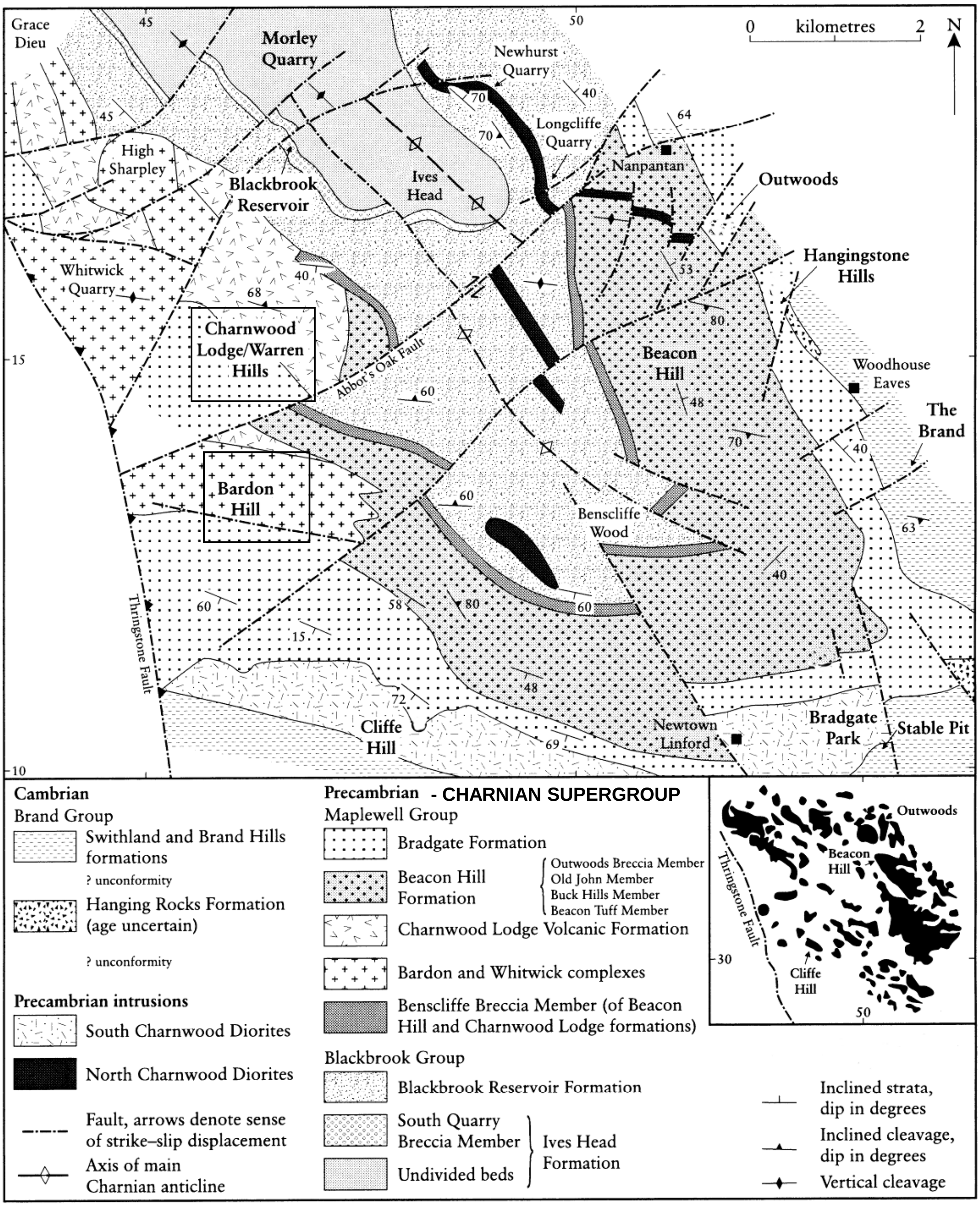


Figure 2 Geology of Charnwood Forest, showing the location of Charnwood Lodge and Bardon Hill. Inset at lower right shows actual outcrops of Precambrian and Cambrian rocks (black), separated by Triassic ‘cover’ strata (from Carney, 1999)

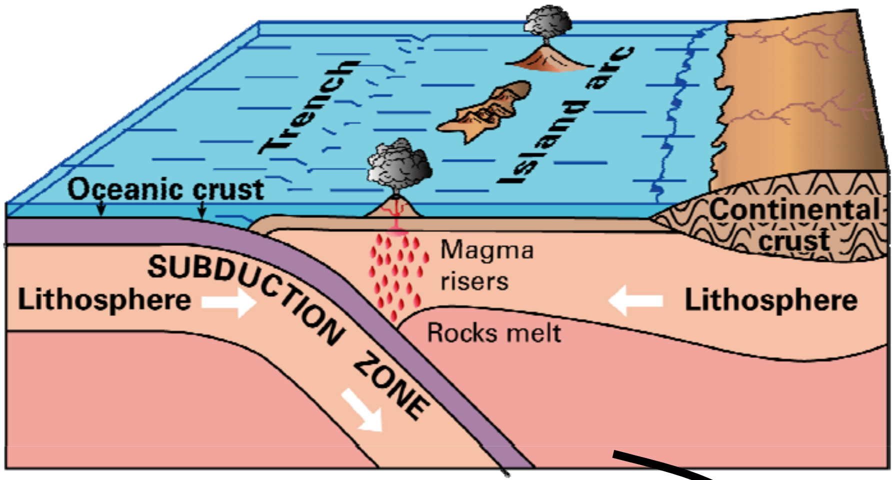
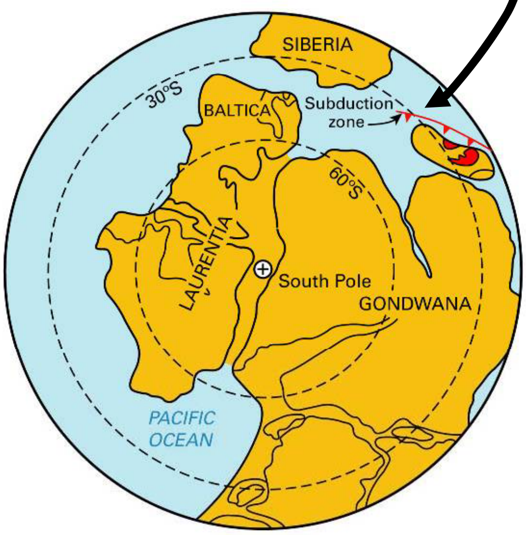


Figure 3 Subduction zone with volcanic arc

Figure 4a Position of England and Wales about 600 million years ago



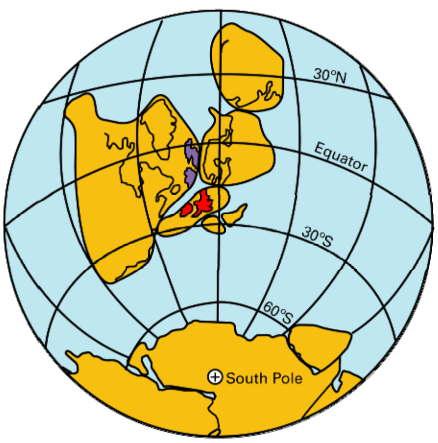


Figure 4b Position of the UK about 420 million years ago
- immediately before the 'plate tectonic unification' of England and Scotland

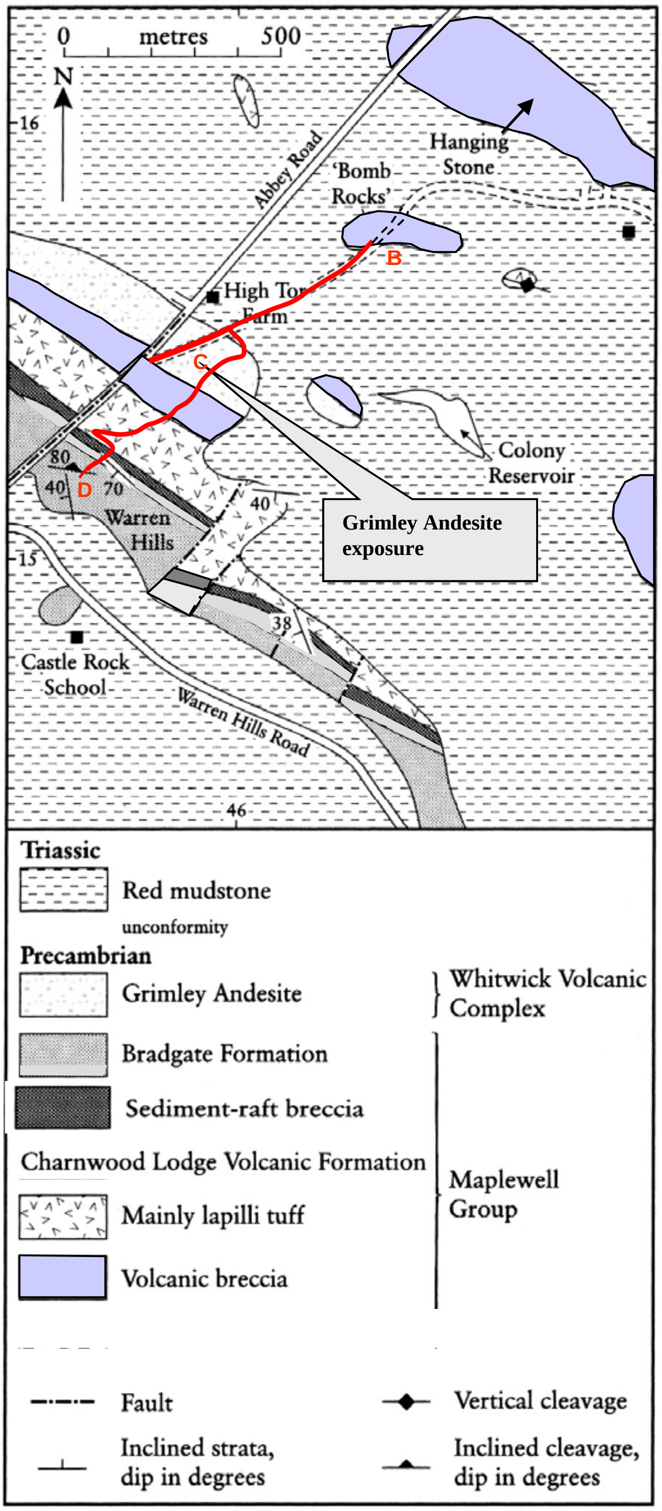
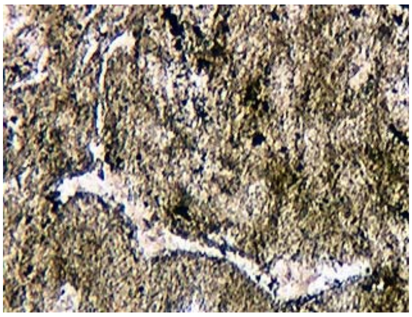


Figure 5. Geological sketch map of part of the Charnwood Lodge Nature Reserve (modified from Carney, 2000b). The red line shows the route followed to localities B-D

Figure 6 A selection of modern volcanic bombs (from BGS collections)

Figure 7 Volcanic breccia at the 'Bomb Rocks'



A microscopic fragment (shard) of volcanic ash from Beacon Hill

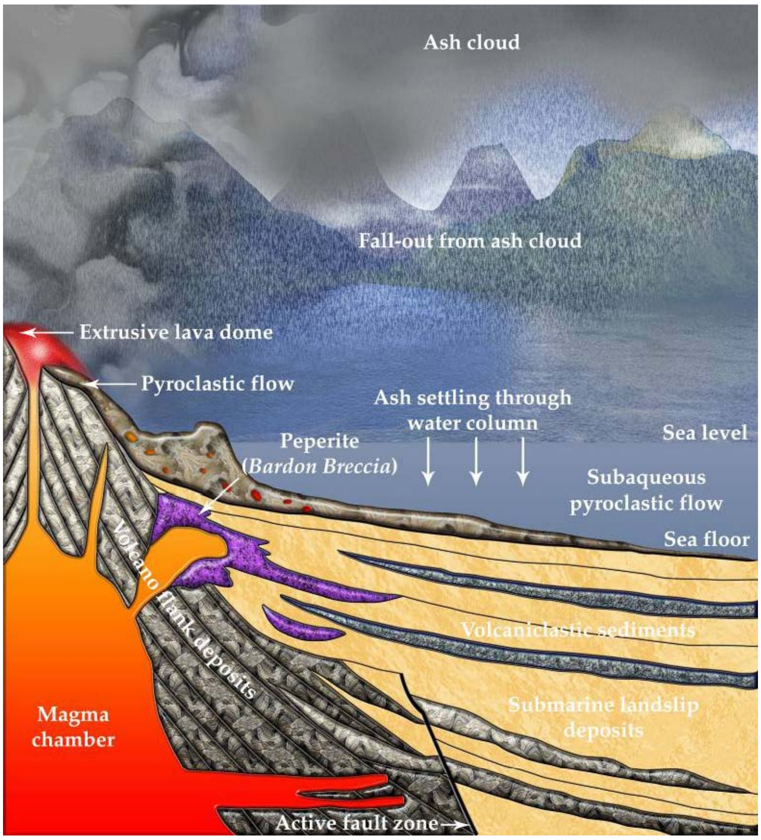


Figure 8. Cross-section through a Charnian volcanic centre

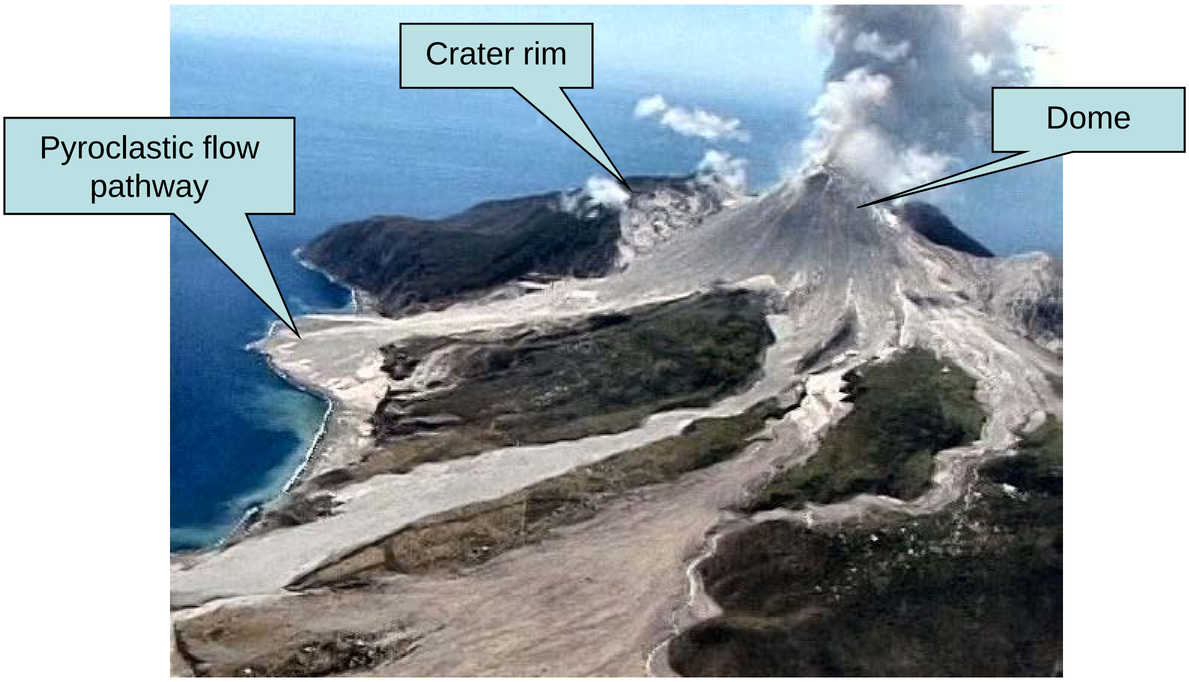


Figure 9. The Soufriere Hills volcano, Montserrat, c. 1997, showing summit crater, volcanic dome and pathway followed by pyroclastic flows

Figure 10. Scenery and exposures at Warren Hills, viewed southwards from Abbey Road

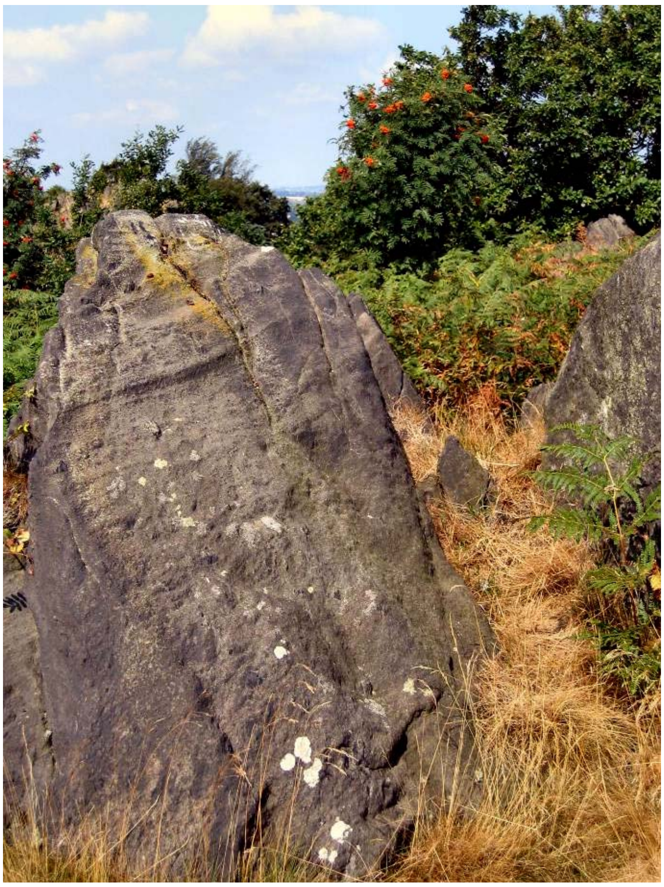


Figure 11. Bedded volcanic-rich strata at the Middle knoll

Figure 12. Panorama looking westwards into Bardon Hill Quarry, showing the Triassic unconformity (see also, Front cover). The summit ridge with trig point is to the left

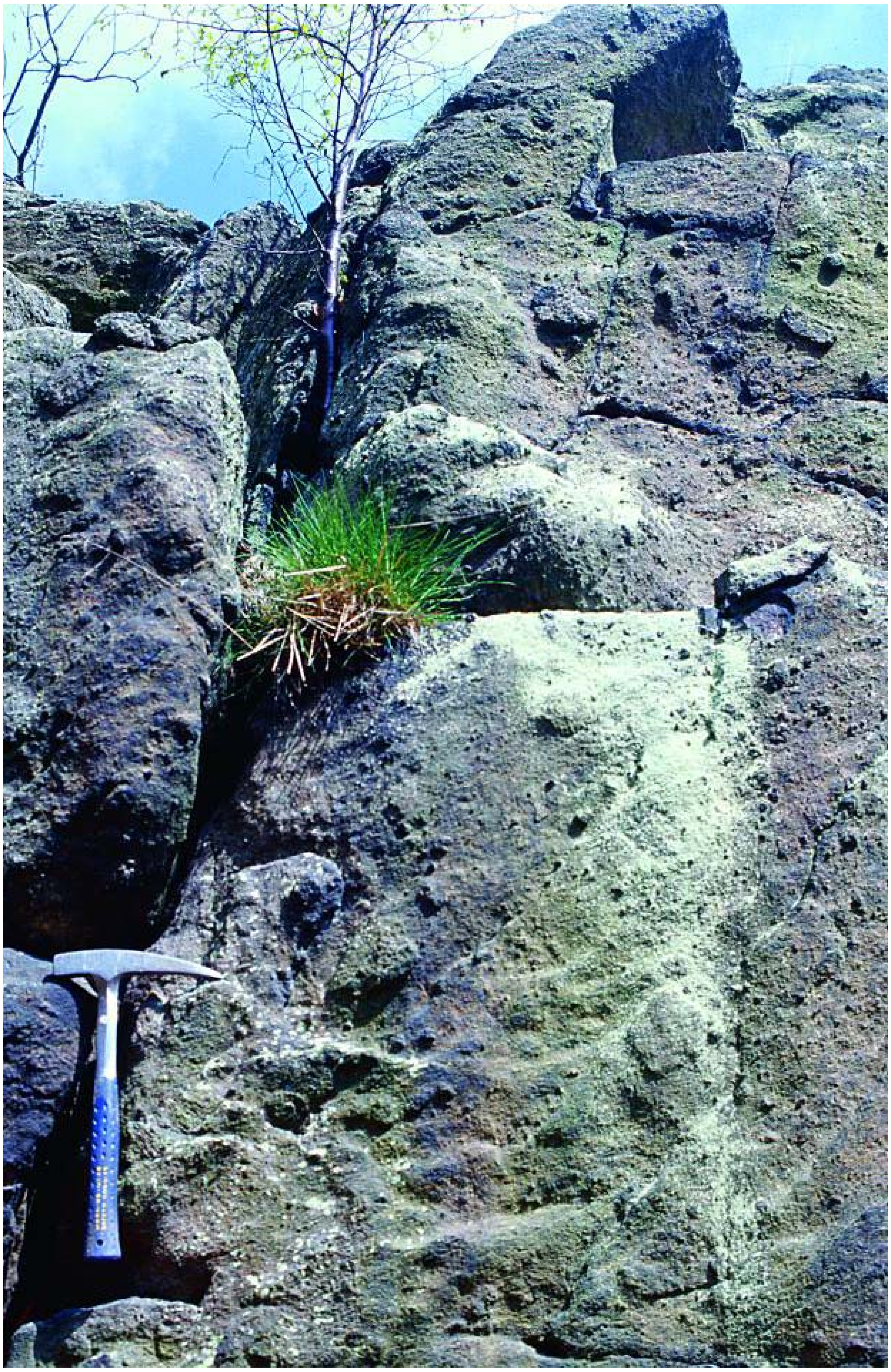


Figure 13. Natural exposures of the Bardon Breccia on the south side of the summit ridge

Figure 14. Examples from the northern exposures in Bardon Hill Quarry, showing interaction between the Peldar Dacite and wet, sea-floor sediments of the Bradgate Formation.

Above, porphyritic dacite (dark grey, with phenocrysts) invades mudstones and siltstones showing contorted lamination.

Right, ‘Peperite’ formed by thorough intermixing between wet sediment (yellow-brown areas) and dark grey porphyritic dacite with large ‘glassy’ quartz phenocrysts. The specimen, 7.5 cm in length, is also featured in Carney (1999).