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GUIDE TO THE GEOLOGY OF BRADGATE PARK AND SWITHLAND WOOD, CHARNWOOD FOREST

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Including a provisional itinerary and details of localities

Old John Tower, with south-dipping strata of the Beacon Hill Formation in the foreground

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PROVISIONAL ITINERARY AND NOTES

Gather at Bradgate Park, Hunt's Hill entrance (SK 5232 1167)

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Note:

Due to recent vandalism and attempted theft of *in situ* fossils, by person(s) unknown, a protocol was established between the BGS and the Bradgate Park Trust. This requires that the organiser of the geological group that wishes to visit should provide an advance written notification to the Estate Office at Bradgate Park. In cases where the group is to be led by a member of the BGS, the organiser should mention this and give the name of the BGS person involved. **The Trust will decide on whether or not the fossil site can be visited,** and under what conditions such a visit is undertaken. The Trust may ask the organiser for a small donation, which usually works out to about £1 per head for a group of 20. This arrangement is not enforced in the case of small parties of genuine researchers who wish to visit, but it is still recommended that the Trust be notified in advance.

***Historical note**: Bradgate House was the childhood home of Lady Jane Grey, the ill-fated '9-day' Queen of England. Jane Grey possessed royal blood through her grandmother, Princess Mary Tudor, sister of Henry VIII, and this heritage brought about her downfall in 1554. In Henry VIII's will, Jane had been named heiress to the English throne, but only if his son Edward and daughters Mary and Elizabeth died without issue. But the sickly Edward VI ruled for just six years and his ambitious advisor, John Dudley, was determined to remain in power. To that end, he persuaded Edward, who was only 16, to write a 'Devise for the Succession' and name his cousin, Jane Grey, as heir. Though just fifteen at the time, she was known for her Protestant piety and learning and it was this religious devotion which persuaded Edward to alter the established legal succession. Deeply pious himself, he could not leave the throne to his half-sister Mary, the staunchly Catholic daughter of Katherine of Aragon. Jane was quickly wed to Dudley's son, Guilford, and crowned Queen of England in July 1553. But she ruled for just nine days (some say 13), trapped and unhappy. Mary Tudor mustered a small army and claimed the throne with great popular support and Jane was imprisoned in the Tower of London. Her subsequent execution was an unwanted political necessity for Mary, who was faced with a rebellion that threatened her plans to marry Philip II of Spain. At the age of seventeen Jane met her end in the Tower with great dignity and courage. Many of the ancient oak trees around Bradgate House were pollarded long ago, and legend has it that this was done as a response to Jane's beheading.*

A. INTRODUCTION AND GEOLOGICAL BACKGROUND

Charnwood Forest is one of the few parts of England where there are exposures of 'basement' rocks dating back to Precambrian time. Its locally rugged topography is caused by these highly resistant rocks protruding as craggy knolls through a surrounding cover of Triassic-age Mercia Mudstone strata and Quaternary deposits. Past workers have viewed Charnwood Forest as a 'fossil' hill range that was carved by erosion dating from the late Carboniferous (end-Variscan) block uplifts, was subsequently buried beneath Triassic and younger strata, and is now in the process of being exhumed.

The 'hard rock' outcrops and distinctive scenery of Charnwood Forest, exemplified by Bradgate Park, have attracted much interest over the centuries, and Watts (1947) charts a number of publications stretching back to 1790. The lithostratigraphy of the Charnwood Forest succession was formalised after the detailed mapping and thesis of Moseley (1979), and a subsequent paper by Moseley and Ford (1985). Figure 1 shows that the Charnian Supergroup *sensu stricto* is divided into two principal groupings, of which the youngest, the Maplewell Group, will be visited today (localities and route are shown in Figure 2). In Swithland Wood, the strata to be visited belong to the Brand Group. This overlies the Maplewell Group, and as it is now referred to the Lower Cambrian, rather than to the Precambrian as previously thought, it is no longer included as part of the Charnian Supergroup.

A *Precambrian* age (i.e. older than the start of the Cambrian Period, 543 million years ago) for the Charnian rocks was hinted at as long ago as 1865. It was finally confirmed following the work of Lapworth (1882), although his observation was based on similarities between Charnian rocks and the Caldecote Volcanic Formation, which is demonstrably overlain unconformably by Lower Cambrian strata at Nuneaton, 30 km to the west. Lapworth's discovery had major implications for something that happened much later - the finding of fossils in the Charnian strata by a schoolboy, Roger Mason, when out climbing near Woodhouse Eaves in 1957. Since then, several more fossiliferous localities have been found in Charnwood Forest (eg. Boynton and Ford, 1995), including the important exposure in Bradgate Park. Their significance to Precambrian geology, and to the understanding of the early evolution of organized life, will be discussed later on.

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 560 - 566 Ma (Compston et al., 2002) have been determined for the fossil-bearing upper part of the Maplewell Group on the basis of isotopic analyses that measure the decay of uranium to lead in rock-forming minerals such as zircon. Given the exposed thickness of 3000 m for the Charnian sequence, however, it is clear that more isotopic determinations will be needed in order to constrain the entire age-range of the succession.

Mode of origin of the Charnian Supergroup

Evidence concerning the mode of formation of the Charnian sequence is at first sight contradictory. In the south and east - for example in Bradgate Park - the rocks are typically well stratified and of obvious sedimentary origin. When looked at under the microscope, however, the grain constituents – mainly volcanic rock fragments, crystals (plagioclase and quartz) and volcanic ash shards – point to a wholly volcanic, andesitic to dacitic source region. 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 (top right of Figure 6), 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.

Evidence for the **depositional environment** of these rocks is provided by *sedimentary structures* seen in the stratified parts of the Charnian Supergroup. At Bradgate Park, for example, the absence of features such as cross-bedding or current and wave-ripple structures suggests that deposition occurred well below storm-wave base (ie. >50 m depth). Instead, sedimentary structures such as grading, loading and slump-induced disruption of bedding indicate that they accumulated by processes that involved the transport of volcanic detritus in sediment-laden submarine flows (turbidity currents). Earthquakes caused by tectonic or volcanic activity probably triggered individual sedimentary flow-events. Finally, marine (oceanic) environments are further suggested by the types of fossil seen in Charnwood Forest.

The Maplewell Group strata contain the greatest volume of pyroclastic material, including ash fragments, and these 'tuffaceous' rocks were therefore formed during the time of maximum volcanic activity. As Figure 1 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 (to be seen at Bradgate Park) into the thickly-developed and very coarse *volcanic breccias* of the Charnwood Lodge Volcanic Formation, which have been interpreted as pyroclastic flow deposits (Carney, 2000a). This indicates that the Maplewell Group volcanoes (Figure 6) were located in the north-west of Charnwood Forest, where there are also rocks that could represent actual feeder zones or conduits to the vents. These rocks 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 (Figure 1). They are not exposed in this part of Charnwood Forest; however, distinctive blocks of porphyritic dacite, featuring a dark grey groundmass with large plagioclase and quartz phenocrysts, can be seen in the walls of the toilets at the Hunt's Hill and Hall Gates (Cropston) entrances to the Park. These specimens are of the Peldar Dacite Breccia and were quarried from the Whitwick Volcanic Complex of north-western Charnwood Forest (Figure 1).

The **plate-tectonic environment** in which the Charnian rocks were formed can be partly deduced from rock chemistry (silicate and trace element analyses). These chemical studies indicate that the Charnian magmas have compositions appropriate to their generation above a subduction zone, shown diagrammatically in Figure 3, within an arc of volcanic islands surrounded by an ocean (Pharaoh et al., 1987). Palaeomagnetic rock measurements at Nuneaton (Vizan et al., 2003) further demonstrate that this late Precambrian volcanic arc was located close to the southern tropic, just off the margin of the Gondwana continent (Figure 4a). Modern oceanic arc systems, such as the Caribbean islands, are largely submerged and consequently the fragmental material, either eroded or ejected from the volcanoes, would have accumulated on the surrounding sea floor, a good modern analogy being the island of Montserrat (Figure 5). This is therefore the *palaeoenvironment* envisaged for the rocks of the Charnian Supergroup (Figure 6).

Charnwood Forest as a 'young' mountain range

The last major events to affect the Charnwood basement involved the formation of the *Charnian anticline* (Figure 1), and also a highly penetrative west-north-westerly *cleavage*, which is visible in many exposures at Bradgate Park. 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, showing that they were not formed in Precambrian time. Instead, the cleavage formed as a result of compression during the Caledonian orogeny (mountain-building), which in this part of Britain climaxed towards the end of the Silurian Period, at about 420-416 Ma (Carney et al., 2008). This event was a prelude to the late Caledonian (Acadian) plate tectonic movements (about 397 Ma) that closed the Iapetus Ocean, in the process uniting southern Britain with Scotland (Figure 4b). A major reverse fault – the *Thringstone Fault* – defines the western edge of Charnwood Forest (Figure 1). This fault was formed during the Caledonian orogeny, but has moved repeatedly since, ensuring that the Charnwood basement rocks have always remained relatively close to the surface. To the west, the North-west Leicestershire Coalfield consists of Carboniferous strata that were preserved on the downthrown side of the Thringstone Fault.

B. LOCALITY DESCRIPTIONS (Figure 2)

Bradgate Park is a local conservation area of rolling heathland studded with craggy knolls. Its size, and the fact that it contains palaeontological localities of international importance, justifies its status as one of the principal Charnwood Forest geological sites. In addition, many of its exposures serve as type sections for units within the Maplewell Group. Late Precambrian intrusions belonging to the South Charnwood Diorites occur in the south of the Park but their contacts with the adjacent stratiform sequence are unexposed.

The importance of this area is reflected by its frequent mention in the geological accounts of Charnwood Forest by W W Watts. The principal reference works, however, are the guides to Bradgate Park by Sutherland et al*.* (1987, amended and reprinted in 1994), McGrath (2004) and Ambrose et al. (2007). This Guide is based on the circular walk given in the latter map and booklet. It commences in the Beacon Hill Formation, and proceeds to stratigraphically younger strata of the Bradgate Formation, Hanging Rocks Formation and Brand Group.

1: Beacon Hill Formation, crags around Old John Tower (SK 5255 1131)

The oldest Charnian unit at Bradgate Park is the Beacon Hill Formation, and this locality represents the type section of its uppermost component – the Old John Member (Moseley, 1979), which comprises the crags around the hill crowned by the Old John Tower (Front cover). The lower crags show parallel-laminated to medium-bedded alternations of tuffaceous mudstone, siltstone and sandstone. Delicate shards of volcanic ash, of microscopic size (e.g. Fig. 6), are commonly preserved in this formation. The most prevalent sedimentary structures are graded bedding and various types of soft-sediment deformation. The latter is particularly well demonstrated on polished surfaces along the footpath through these crags. It is seen as gently wavy bedding, rafted and truncated bedding or laminae, and load structures formed where lobes of sandstone penetrate downwards into mudstone or siltstone. On higher crags there are larger-scale examples of disrupted bedding and convoluted bedding, the latter confined within a c. 40-80 cm interval sandwiched between undeformed sedimentary layers. On the traverse to the south, over the crown of the hill on which the Old John Tower is located, there are several examples of beds with partially to completely disrupted mudstone layers. This may suggest that the Sliding Stone Slump Breccia (see below) is just one (particularly distinctive) horizon within a much thicker interval recording instability within the Charnian sedimentary basin.

The intensely penetrative, west-south-west trending Charnian cleavage is well displayed on these crags. Although dominantly subvertical in attitude, it shows refraction where passing through sedimentary layers of differing grain size.

Interpretation: The absence of significant cross-bedding and ripple marking indicates that these strata were deposited below storm wave-base (i.e. below about 50 m depth). Graded bedding is indicative of deposition from turbidity currents, although at least some of the sedimentary material was also probably contributed by the settling of volcanic ash through the water column. Slumped or contorted bedding and load structures are post-depositional features, the formation of which must have occurred within a rapidly deposited pile of sediments that had not been completely dewatered. Highly convoluted beds, confined to narrow intervals, are reminiscent of 'seismites', caused by the action of earthquake-induced movements on particularly susceptible unconsolidated sedimentary layers.

2: Bradgate Formation: Sliding Stone Slump Breccia (SK 5304 1133)

As noted earlier, this unit is part of a much thicker interval of syn-sedimentary disruption in this part of the sequence. Exposures demonstrating its 'strike' are encountered as a line of small crags to the south of Locality 1, and can be followed eastwards towards its main locality (2). The latter is the type section and most spectacular development of the Sliding Stone Slump Breccia, the basal bed of the Bradgate Formation. It shows abundant contorted rafts of laminated mudstone, one of which is called the 'Swiss Roll', some up to 0.6 m long, separated by coarse-grained volcaniclastic sandstone devoid of structure. There are also rare instances of mudstone fragments with constricted or 'hour glass' shapes, particularly on fallen blocks on the south side of this locality.

The sequence fines upwards, over 9 m of vertical section, and just below the topmost bedding plane, up the slope on the eastern edge of the exposure, can be seen unusual 'sag-structures', consisting of thin beds and laminae that exhibit marked downwarping, and slight concomitant thickening, within three funnel-like structures. The most prominent of these is a few centimetres across and about 12 cm deep. Close examination indicates that it is in part bounded by syn-sedimentary microfaults (Figure 7), and that sedimentary laminae close to the base of the sag show intense brecciation. In all three structures, the basal parts appear to 'root' within the same thin bed of medium-grained volcaniclastic sandstone.

Interpretation. The Sliding Stone Slump Breccia forms part of a sedimentary event-package and has many features in common with graded turbidite beds characterised by a thick, coarse-grained basal facies (Bouma division A), here represented by the abundance of large sediment rafts. Sutherland et al. (1994) concluded that this basal breccia component originated as a subaqueous sediment gravity flow. It is envisaged that initially, a succession consisting of muddy beds within a predominantly sand-rich sedimentary sequence was accumulated, probably rapidly and from turbidity currents flowing down a gentle slope. The sequence remained water-saturated and subsequently it became gravitationally unstable, perhaps due to a shock-wave generated by an earthquake. This resulted in slumping and downslope movement involving whole packages of beds – a submarine landslide (Figure 6). The sandy beds would have been loosely consolidated and thus were readily liquefied, breaking down into a slurry of grains. The intercalated mud - rich layers, which are now seen as the contorted rafts, would have retained less pore-water and were thus relatively coherent. They deformed plastically, resulting in folding and contortion, and were broken up by the internal stresses exerted during *en masse* flowage of the enclosing liquefied sand. The small sedimentary fragments with constricted, or 'hour glass' shapes are interpreted as relics from the initial, 'sliding' part of the slump, during which tensional stresses acting on plastically deforming mudstone beds would have stretched them and pulled them apart, a process called 'necking'. The chaotic nature of the present exposures represents a later stage, when the slump was coming to rest and material from higher up the slope was piling into, and thus compressing, the largely stationary front of the sediment mass.

Explanations for the 'sag' structures have ranged from volcanic bomb-impacts, to burrows, and to disturbances produced by the escape of trapped water or gases along the sandstone layer that intersects the bases of the sags. This area originally lay at an estimated 14 km from the active volcanic centres, ruling out an explanation as a bomb-sag. Furthermore, deeply penetrating burrows are unknown in the Precambrian world-wide. Close examination suggests that these structures may have been initiated along a faulted syn-sedimentary flexure that 'roots' downwards into a movement zone (decollement) represented by the surface of the thin sandstone bed noted above (Figure 8). The structure is a further indication of instability within unconsolidated, and still water-saturated sediments on the sea-floor.

2a: Bradgate Formation above the Sliding Stone locality *(optional)*

These prominent crags (SK 5317 1114) are in southerly-dipping strata of the Bradgate Formation, overlying the Sliding Stone Slump Breccia. The principal feature here is the presence of repetitive normal grading, which is indicated by a number of turbidite beds stacked in vertical sequence. Each turbidite consists of a lower facies of medium-grained volcaniclastic sandstone, which fines upwards through siltstone into an upper capping of laminated to massive mudstone. The succession is interpreted as evidence for short-periodicity instability within the depositional basin.

Note that the Charnian cleavage changes its angle (is refracted) through this succession, due to changes in the physical response of sandstone, siltstone and mudstone to compression.

3: Swithland Formation, Swithland Wood *(optional)* (SK 5393 1210)

The Swithland Formation is equivalent to rocks formerly known as the 'Swithland and Groby Slates'. It forms the uppermost unit of the Brand Group, the age of which has been the subject of recent controversy. Originally, it was thought to be part of the Precambrian succession – and therefore was placed at the top of the Charnian Supergroup. A Cambrian age for Brand Group is now more likely, however, due to the discovery of the Phanerozoic trace fossil *Teichichnus* in local headstones that had been cut from the Swithland Formation (Bland and Goldring, 1995). These traces can be seen, for example, in the churchyard at Ratby (SK 5129 0593). The contact with the underlying Hanging Rocks Formation is nowhere exposed, although in the Hangingstone Hills section, north of Woodhouse Eaves, the two units appear to be gradational and structurally conformable. An intervening unconformity was nevertheless favoured by McIlroy et al. (1998).

In Swithland Wood, the Swithland Formation largely consists of cleaved silty mudrocks, with detrital constituents of quartz, feldspar and fine-sand grade lithic fragments in a matrix of white mica and chlorite (Worssam and Old, 1988). Bedding and lamination are expressed by variations in these constituents, with white mica preferentially developed along the sub-mm spaced Charnwood cleavage.

Interpretation: The slates originated as silts and muds that accumulated in quiescent, offshore environments on the floor of a sea (the Iapetus Ocean) that had transgressed across the eroded Charnian rocks early in Cambrian times. Because they are so fine-grained, they responded to mountain-building pressures during the end-Silurian orogeny (p. 5) by developing a regular, very closely spaced cleavage. This enabled the rocks to be split and to be used as roofing slates for many of the buildings in Charnwood Forest.

Swithland slates have had a number of specialised uses, for roofing, wall stone and, most famously, for headstones. They are characteristically purple, dark grey or green-grey in colour and are well displayed on the roofs of houses in Woodhouse Eaves, Newtown Linford and in surrounding villages. Swithland slate debris has also been found at Roman sites in Leicester and at East Bridgford, Nottinghamshire (*Margidunum*). The rather coarsely developed cleavage made these rocks difficult to split and dress and they are, therefore, thicker and rougher than Welsh slates, which had largely replaced them by the late nineteenth century. Interest in quarrying these rocks had ceased by 1908 (Ramsey, 2007); however, intricately lettered and carved

Swithland headstones survive in many local church graveyards and can be distinguished from the Welsh slate imports, some of which can be similar in colour, by the presence of characteristic natural undulations on the commonly unpolished back surface of the roughly cleaved slabs. One of the principal slate quarries was here, at the ‘Great Pit’, which was worked to a depth of 180 ft. (55 m) - the stone blocks had to be raised to ground level before being split, sawed and polished.

4: Hanging Rocks Formation (SK 5417 1094)

The feature that sets this unit apart from the rest of the Charnian Supergroup, is its content of conglomerate beds, with their commonly well-rounded volcanic pebbles. Its stratigraphical assignation *vis a vis* to the Maplewell and Brand groups is in some doubt, but here it is placed at the top of the former because certain of the finer grained beds contain shards of volcanic ash, indicating deposition during a late continuation of Charnian volcanism. In the past, however, this formation has been included in the overlying Brand Group (Moseley and Ford, 1985), though bounded above and below by unconformities (McIlroy et al., 1998). The type section and only other known locality for the unit occurs farther north, at the Outwoods/Hangingstone Hills SSSI (Carney, 2000b).

In Bradgate Park, 7.4 m of these strata are exposed at the foot of the slope east of Coppice Plantation. A structural dip of about 70^{o} to the east is suggested by the attitude of coarse partings interpreted as bedding planes. A preferred orientation of spindle-shaped conglomerate pebbles defines a fabric dipping at about 75^{o} to the NNW. This fabric is deceptive; it is not depositional, but is due to later stretching in the plane of the Charnwood cleavage. The westernmost part of the exposure consists of 3.4+ m of grey, medium- to coarse-grained volcaniclastic sandstone with pebbly lenticles, the latter demonstrating that this bed is part of the Hanging Rocks Formation, rather than the underlying Bradgate Formation. A similar sandstone is also found in the southern (topographically lowest) part of the exposure; its stratigraphical position with regard to the conglomerates is therefore in some doubt. The conglomerates forming the main part of the exposure are very poorly sorted and have no internal structure. Most pebbles fall in the size range of 5-15 mm, but larger pebbles, up to 10 cm across, are rather more sporadic in occurrence and in the thickest (1.3 m) conglomerate bed are concentrated in the upper 0.5 m. Sampling is not allowed here, but a close examination suggests an abundance of pink to cream pebbles with sporadic quartz phenocrysts. These are identical to pebbles from the Hangingstone Hills exposures; the latter include fine-grained dacitic tuff and welded tuff (Carney, 2000b) which are, however, unlike any of the lithologies found elsewhere in the Charnian Supergroup. For example, close inspection shows that flow-banding is prominent in some of the larger pebbles at the present locality.

Large fragments (c. 0.4 m across) of pale to dark grey mudstone can also be seen, at the base of the topmost conglomerate bed.

A notable feature of this exposure is the low topographical position of the Hanging Rocks Formation, relative to older strata of the Bradgate Formation (Hallgate Member), occurring on the hillside several metres above. The two alternative explanations for these field relationships discussed in Sutherland et al. (1994) were either that these beds lie within the Bradgate Formation, or that here the Hanging Rocks Formation is occupying a channel cut into the latter. The explanation preferred here is that the Hanging Rocks Formation conformably, and possibly gradationally, overlies the Bradgate Formation (Table 1), but has been faulted against it (Figure 2). The steep dip observed for these beds certainly suggests structural complexity and would in any case be at odds with a channel-fill interpretation. It is noteworthy that exposures of similar conglomerates have recently been confirmed in Coppice Plantation, to the north-west of this locality. Special permission is needed to enter this area, but further investigation is certainly warranted as it may provide further insight on the nature of the transition between the conglomerates and the underlying Bradgate Formation, which is now discussed.

Interpretation: The roundness of many pebbles in the Hanging Rocks Formation indicates a significant degree of transport and reworking of pre-existing volcanic rocks, most probably in rivers or along a shoreline that fringed a volcanic landmass undergoing erosion. Being composed of hard, silica-rich volcanic material, the pebbles survived such reworking, but were then rapidly transported into deeper waters, perhaps as a result of storm activity or earthquake-induced slumping. An ultimate, deep-water environment of deposition (as opposed to fluvial or shoreline environments) is indicated by the poor sorting and matrix-supported nature of the conglomerates, their general lack of organization and, at the Hangingstone Hills locality (Carney, 2000b), the presence of parallel stratification. All of these features suggest a final episode of transport by subaqueous sediment gravity flowage in turbidity currents, with eventual deposition in submarine fan or fan-delta environments. The formation is thus strongly reminiscent of a marine, flysch-type of association, suggesting that the source region was undergoing uplift and erosion. This could signify a tectonic episode that ultimately terminated the Charnian arc; however, volcanism had not entirely ceased since pristine, ashy material occurs in the equivalent strata at the Hangingstone Hills locality (Worssam and Old, 1988; McIlroy et al., 1998; Carney, 2000b). If this reflects the waning stages of Charnian (ie Precambrian) magmatism, then the Hanging Rocks Formation should logically be included at the top of the Charnian Supergroup, rather than as an unconformity-bounded unit at the base of a Brand Group, since the latter contains the Swithland Formation of probable Lower Cambrian age (eg McIlroy et al., 1998).

CAMBRIAN	**BRAND GROUP**	Swithland Formation
		Brand Hills Formation, including Stable Pit Member
		- Unconformity-
PRECAMBRIAN	**MAPLEWELL GROUP**	Hanging Rocks Formation
		Bradgate Formation etc

Table 1. Summary of inferred relationships at the top of the Charnian succession

5: Bradgate Formation at Coppice Plantation (SK 5406 1085)

This small quarry, near the southern margin of Coppice Plantation [SK 5406 1088], exposes about 3 m of volcaniclastic mudstone and siltstone. Individual beds are up to 20 cm thick and are internally massive, though separated from adjacent beds by prominent laminated intervals between 2 and 4 cm thick. Some beds coarsen downwards to thin basal sandstone layers, the latter showing cross lamination and convoluted lamination. Under the microscope, siltstone laminae are crammed with angular fragments of quartz and plagioclase feldspar, whereas the very fine-grained 'mud' layers contain unresolvable grainy material that may represent highly comminuted, and partly degraded or recrystallised, volcanic ash.

Interpretation: These beds were deposited as distal turbidites at a time when volcanic activity was beginning to decline, probably just before the movements that resulted in the influx of pebbly material in the Hanging Rocks Formation. Cross-lamination in some basal sandstone layers could indicate bottom-current activity during deposition of the turbidite, rather than being due to wave or tidal reworking in shallow (i.e. above storm wave-base) conditions. Deposition of the laminated intervals by ash fall-out from distant volcanic eruptions cannot be entirely ruled out.

6: South Charnwood Diorite - Bradgate House (SK 5346 1013)

The South Charnwood Diorites represent the final episode of Precambrian magmatism in Charnwood Forest. The exposures near Bradgate House, home of Lady Jane Grey (see 'historical note' p. 3), are in medium- to coarse-grained, inequigranular diorites, with a highly distinctive mottled pink-grey texture. The pale green, rectangular crystals consist of partly altered plagioclase feldspar, and the dark grey areas are aggregates of mafic minerals (mainly secondary amphiboles and chlorite). They are enclosed within pale pink, very fine-grained granophyric intergrowths of quartz and K-feldspar. Note that these rocks are fractured, quartz-veined and slickensided, but have resisted the penetrative cleavage deformation seen in the other exposures.

The South Charnwood Diorites were named `markfieldite' by Hatch (1909), but Wills and Shotton (1934) preferred `granophyric diorite' as the more accurate term. It has commonly been assumed that these intrusions were emplaced into all of the Charnwood Forest basement sequence. However, the youngest definite intrusive contacts are against strata equated with the Bradgate Formation of the Maplewell Group. The South Charnwood Diorites have not been proved to cut the Brand Group, the basal sandstones of which (in the Brand Hills Formation) locally contain granophyre pebbles that are geochemically and petrographically identical to the South Charnwood Diorites (McIlroy et al., 1998). Erosional unroofing of these intrusions prior to deposition of the Brand Hills and Swithland formations would therefore be compatible with the Lower Cambrian age recently proposed for those units.

7: Brand Hills Formation, the Stable Pit (SK 5341 0996)

The Stable Pit quarry dates to medieval times and provides some of the most accessible exposures of the Stable Pit Member, which is currently placed within the Brand Hills Formation of the Brand Group (Table 1). This site is of prime importance for demonstrating the sedimentology of strata now thought to be of Lower Cambrian age (e.g. McIlroy et al., 1998). It is the type section for the Stable Pit Member (Moseley and Ford, 1985), although the quartz arenites seen here differ very considerably from the wacke-type sandstones found in the same member at ◇The Brand¤. Their uniqueness in the Charnian was commented on by Watts (1947, p.52) and, given the current debate surrounding these strata, it can be suggested (below) that they are more reminiscent of lithologies in the Hartshill Sandstone Formation, which forms the base of the Lower Cambrian sequence at Nuneaton.

The principal exposures on the northern side of the Stable Pit are in grey- to pink-weathering, medium-grained, grey to white-weathering quartz-rich sandstones (quartz arenites), which have a ◇glassy¤ appearance on fresh surfaces. In this part of the quarry they dip at between 15 and 20^{o} to the north-west. Bedding is rather faint and defined by c. 20 mm thick layers of darker grey sandstone, which outline cosets of low-angle planar cross-bedding, all dips being to the north-west. On certain bed-tops can be seen prominent arcuate features reminiscent of ripples or scour-channels.

A tectonic structure trending roughly east-west, parallel to the local cleavage, is inferred to traverse this quarry because the beds next seen to the south side are vertical to steeply south-dipping (50-60^{o}), in a zone about 8 m wide. Here the sequence is more heterolithic; it includes a thick bed of slaty mudstone with thin (20-30 mm) layers of quartz arenite, passing northwards into alternating beds of quartz arenite and mudstone, and thence to mainly quartz arenite with rafts or discontinuous lenses of mudstone.

A subvertical dyke of fine-grained, altered **diorite,** just over 1 m wide, is intruded into the quartz arenites in the north-west of the quarry. Its east-west trend appears structurally controlled since it is parallel to the local cleavage trend, and to quartz veins traversing the host rocks. The dyke is also parallel to prominent joints characterised by subhorizontal slickenside lineations on the northern side of the quarry. The age of dyke intrusion is not known, but if the Stable Pit Member is indeed Lower Cambrian then it is likely that the dyke was emplaced during the Late Ordovician magmatic event that affected the East Midlands. It may thus be coeval with granodiorites and diorites of the Mountsorrel Complex, located to the east of Charnwood Forest (Carney et al., 2009).

Interpretation: The sections at Stable Pit form part of a highly distinctive but rather restricted facies within the Brand Hills Formation, which is now believed to be of Lower Cambrian age (McIlroy et al., 1998). The unique feature of these lithologies, with respect to other Charnwood rocks, is their grey, glassy and obviously 'clean', quartz-rich character. In fact, these strata compare well with Lower Cambrian strata of the Park Hill Member (Hartshill Sandstone Formation), exposed at Nuneaton in the West Midlands (McIlroy et al., 1998). The occurrence of beds containing thick cosets of tabular cross-bedding is particularly reminiscent of the Park Hill Member (e.g. Carney, 1995). It suggests deposition in nearshore marine environments, which perhaps were developed along or close to the shoreline of the Iapetus Ocean as it began to transgress across the eroded Precambrian ('Avalonian') microcontinent.

8: Triassic exposure opposite the Pheasantry (SK 5317 0987)

This exposure forms part of an old quarry from which the red bricks of Bradgate House are said to have been made; unfortunately it can only be viewed from a distance. The strata consist of blocky to laminated, red mudstones and silty mudstones. They belong to the Mercia Mudstone Group, which was deposited mainly by wind action in a desert that occupied much of the interior of the Pangaea supercontinent in Triassic times. The intercalated grey-green beds are of dolomitic siltstone; in the surrounding area similar beds are commonly ripple marked, have halite (salt) pseudomorphs, and are thought to have been deposited in ephemeral, playa lakes that subsequently dried out due to extreme evaporation.

Throughout the Triassic Period, the East Midlands crust was subsiding and, as a result, these 'red beds' passively buried the older rocks that formed the Charnwood Forest palaeo-mountain range. The original, pre-Triassic valleys can still be seen, however, as they are now being re-excavated due to the preferential erosion of the soft Mercia Mudstone fill. The Lin valley, in which this exposure is situated, is a classic example of this 'fossil' topography, which is best appreciated by considering the low altitude of these Triassic strata, relative to the much older Precambrian rocks occupying the surrounding hill tops.

The Fossil Site

This exposure may be visited under conditions to be agreed in advance with the Bradgate Park Trust (see inside Front cover). In addition to its palaeontological importance, this locality also demonstrates the sedimentary environments that prevailed immediately prior to the growth of a diverse assemblage of Precambrian life. The Sliding Stone Slump Breccia constitutes the 5.5+ m-thick bed forming the base of this sequence. It consists of grey, very coarse-grained to granule-grade volcaniclastic sandstone with sedimentary rafts of highly contorted mudstone or siltstone. The bed fines upwards to diffusely-stratified medium-grained sandstone, which in turn is capped by c. 2.8 m of parallel laminated to thinly bedded volcaniclastic mudstones and siltstones containing sporadic sharp-sided beds of massive sandstone. A further graded sedimentary cycle occupies the upper c. 1.6 m of the crag; it commences with graded, laminated volcaniclastic sandstone and culminates in exceptionally well-laminated mudstones and siltstones, with weak normal grading, immediately beneath the fossiliferous bedding plane.

The fossil-bearing bedding plane covers an area of about 25 m^2 and on it some fifty fossil impressions have been found, though some are very faint and difficult to see except in good oblique sunlight (about 4.15 pm in September is the best time). This bedding plane shows the typical mode of preservation of fossils in Charnwood Forest, as low-relief (ie. ~1 mm or less) impressions on upper bedding surfaces. The impressions have resulted from moderately soft-bodied organisms coming to rest on the silts, with fairly rapid burial pressing them down into the sediment. Counterparts on the under surfaces of overlying beds have not yet been found. Little is seen of the fossils' three-dimensional shape and no hard parts are preserved, although the preservation of some discs indicates that they may have been formed of a stiff, or leathery, organic substance.

The Bradgate Park impressions, described by Boynton and Ford (1995) and Ford (1999, 2000) include several specimens showing complex fronds, designated as *Bradgatia linfordensis.* Other fossils on this bedding plane include an incomplete impression of a large frond, *Charnia grandis*, now 60 cm long but possibly a metre long when complete, as well as a minute cf. *Charniodiscus concentricus* only 17 mm long. There are also a number of disc-like fossils. A selection of fossils from here, and various other localities in Charnwood Forest, is shown in Figure 9. They include the world-famous *Charnia masoni*, which was discovered in the eastern part of Charnwood Forest in 1957. This was the first macrofossil to be found anywhere in the world in strata known to be Precambrian in age. Prior to this, workers thought that strata containing similar fossils, notably those from the Ediacara 'type area' in Australia (see below), must be Cambrian or younger since the ‘conventional wisdom’ of that time was that ‘you couldn’t have fossils in Precambrian rocks’!

***Interpretation of the fossils**:* The Charnwood Forest fossils are the only examples of a truly diverse late Precambrian biota known in Britain and Western Europe, and as such they represent a unique and important aspect of the history of life on Earth. They are regarded as members of the Ediacara biota, named from the localities near Ediacara in the Flinders Ranges of South Australia. Apart from the rich assemblages in the latter, examples of the Ediacara biota have been found in many parts of the world, with Newfoundland perhaps being the most important as the volcaniclastic strata there were deposited in deep waters, similar to the environments postulated for the Charnian Supergroup. Ford (2000) notes that when simple frondose fossils such as *Charnia masoni* were first discovered, their assignation to some form of complex sea-weed was considered. They were later interpreted as probably the traces of organisms comparable with the present-day Pennatulacea (sea-pens), which are primitive colonial cnidarians (coelenterates); however, such a comparison is no longer favoured. Some of the fronds possess basal discs, which represent holdfasts; these also occur in isolation, here and at other localities.

The complex frondose colonies, such as *Bradgatia linfordensis* (Boynton and Ford, 1995), are regarded as having been composed of clusters of fronds radiating from a central attachment. Both simple and complex frondose fossils have been assigned to the extinct phylum ‘Petalonamae’, Class Rangeomorpha, Family Charniidae. Frondose organisms comparable to some of those seen in Charnwood Forest have been recorded at several localities in Newfoundland, Russia, China and Namibia, all in late Precambrian strata.

Many disc-like fossils have been interpreted as medusoids, and thus placed within the Phylum Cnidaria ?Class Cyclozoa, Family Cyclomedusidae. Comparable modern examples of these cnidarians are the sea anemones, corals and jellyfish. Many workers, however, now doubt whether any of these could be ascribed to a ‘jellyfish’ type of organism. Indeed, the affinities of all late Precambrian fossils are still controversial. Thus the reason why we refer the assemblage to an Ediacaran ‘biota’, rather than to a ‘fauna’ is because palaeontologists are still uncertain which species are animals and which are plant-life, or fungi, or indeed any of these groups. Some may even be complex hybrids, or chimera, between coelenterate-like animals, fungi and microbial colonies. Many species almost certainly belong to a kingdom, or kingdoms, of life-forms that died out at the end of Precambrian time (about 543 Ma ago), and therefore cannot be compared to any of the Phanerozoic kingdoms of life. The debate continues to be developed as more fossils are being found, notably by the BGS here in Charnwood Forest, and more sophisticated techniques are used to investigate them.

The Bradgate Park exposures illustrate that that these fossils occur in turbidite-facies volcaniclastic strata, which are generally devoid of structures attributed to tidal or storm-influenced wave or current action and thus may have been deposited in waters exceeding about 50 m depth. Precisely how deep is critical, because below 200 m in modern seas the disphotic zone is entered, where plants cannot grow. As discussed earlier, the dominant sedimentation mechanism involved sediment gravity flowage, which was in part driven by tectonic and/or volcanic events. The beds with fossil impressions seem to represent relatively quiescent periods, characterised by the settling out of suspended fine-grade material, and commonly occur at the very tops of major graded sedimentary packages. This type of deep to moderately deep water environment has been recognised in only a few of the Ediacaran fossil occurrences around the world; for example, in Newfoundland, and is regarded as representative of a marine sedimentary fan situation. In most other occurrences, such as the Ediacaran type locality in the Flinders Range of Australia, there is evidence to suggest that life may have flourished in relatively better lit, nearshore shelf, tide- or storm-dominated environments.

References

AMBROSE, K., CARNEY, J.N., LOTT, G.K., WEIGHTMAN, G. and McGRATH, A., 2007. Exploring the landscape of Charnwood Forest and Mountsorrel. Keyworth, Nottingham: British Geological Survey.

BLAND, B.H. and GOLDRING, R. 1995. *Teichichnus* Seilacher 1955 and other trace fossils (Cambrian?) From the Charnian of Central England. *Neues Jahrbuch for Geologie und Palaeontologie* (Seilacher Festschrift) 195, 5-23.

BOYNTON, H E and FORD, T D. 1995. Ediacaran fossils from the Precambrian (Charnian Supergroup) of Charnwood Forest, Leicestershire, England. *Mercian Geologist*, 13, 165-183.

CARNEY, J N. 1995. Precambrian and Lower Cambrian rocks of the Nuneaton inlier: a field excursion to Boon's and Hartshill quarries. *Mercian Geologist,* Vol. 13, 189-198.

CARNEY, J N. 1999. Revisiting the Charnian Supergroup: new advances in understanding old rocks. *Geology Today*, Vol. 15, 221-229.

CARNEY, J N. 2000a. Igneous processes within late Precambrian volcanic centres near Whitwick, north-western Charnwood Forest. *Mercian Geologist,* Vol. 15, 7-28.

CARNEY, J N. 2000b. Outwoods-Hangingstone Hills. In: *Precambrian Rocks of England and Wales*. Geological Conservation Review Series No. 20. pp. 43-48. Joint Nature Conservation Committee, Peterborough.

CARNEY, J N, ALEXANDRE, P, PRINGLE, M S, PHARAOH, T C, MERRIMAN, R J and KEMP, S J. 2008. ^{40}Ar-^{39}Ar isotope constraints on the age of deformation in Charnwood Forest, UK. *Geological Magazine*, Vol. 145, 702-713.

CARNEY, J N, AMBROSE, K A, CHENEY, C S and HOBBS, P R N. 2009. Geology of the Leicester district. *Sheet description of the British Geological Survey*, 1:50 000 series Sheet 156 (England and Wales).

COMPSTON, W., WRIGHT, A.E., and TOGHILL, P. 2002. Dating the Late Precambrian volcanicity of England and Wales: Journal of the Geological Society, London, Vol. 159, p. 323-339.

FORD, T D. 1999. The Precambrian fossils of Charnwood Forest. *Geology Today*, Vol. 15, 230-234.

FORD, T D. 2000. Precambrian palaeontological sites: Charnwood Forest. In *Precambrian Rocks of England and Wales*. Geological Conservation Review Series No. 20, Joint Nature Conservation Committee, Peterborough. 185-193.

HATCH, F H. 1909. *Text-book of Petrology*, London.

LAPWORTH, C. 1882. On the discovery of Cambrian rocks in the neighbourhood of Birmingham. *Geological Magazine* (2), Vol.9, 563-565.

MCGRATH, A.G. 2004. A Geological walk around Bradgate Park & Swithland Wood. Published by the British Geological Survey on behalf of ODPM and MIRO.

McILROY, D, BRASIER, M D, and MOSELEY, J M. 1998. The Proterozoic-Cambrian transition within the 'Charnian Supergroup' of central England and the antiquity of the Ediacara fauna. *Journal of the Geological Society of London,*Vol. 155, 401-413.

MOSELEY, J. 1979. The geology of the Late Precambrian rocks of Charnwood Forest. Unpublished PhD Thesis, University of Leicester.

MOSELEY, J, and FORD, T D. 1985. A stratigraphic revision of the late Precambrian rocks of Charnwood Forest, Leicestershire. *Mercian Geologist*, 10, 1-18.

PHARAOH, T C, WEBB, P C, THORPE, R S, and BECKINSALE, R D. 1987. Geochemical evidence for the tectonic setting of late Proterozoic volcanic suites in central England. 541-552 in *Geochemistry and Mineralization of*

Proterozoic Volcanic Suites. PHARAOH, T C, BECKINSALE, R D, and RICKARD, D (editors). Geological Society of London Special Publication, No.33.

RAMSEY, D. 2007. New light on early slate & granite extraction in North-west Leicestershire. *Leicestershire Industrial History Society* Bulletin 18, 3-79.

SUTHERLAND, D S, BOYNTON, H E, FORD, T D, Le BAS, M J, and MOSELEY, J. 1994. A Guide to the geology of the Precambrian rocks of Bradgate Park in Charnwood Forest, Leicestershire. *Transactions of the Leicester Literary and Philosophical Society*, **87** (Revised Edition). 36pp.

VIZAN, H, CARNEY, J N, TURNER, P, IXER, R A, TOMASSO, M, MULLEN, R P, and CLARKE, P. 2003. Late Neoproterozoic to Early Palaeozoic palaeogeography of Avalonia: some palaeomagnetic constraints from Nuneaton, central England. *Geological Magazine*, 140, 685-705.

WATTS, W W. 1947. *Geology of the ancient rocks of Charnwood Forest, Leicestershire.* Leicester: Leicester Literary and Philosophical Society.

WILLS, L J, and SHOTTON, F W. 1934. New sections showing the junction of the Cambrian and Precambrian at Nuneaton. *Geological Magazine*, Vol.71, 512-521.

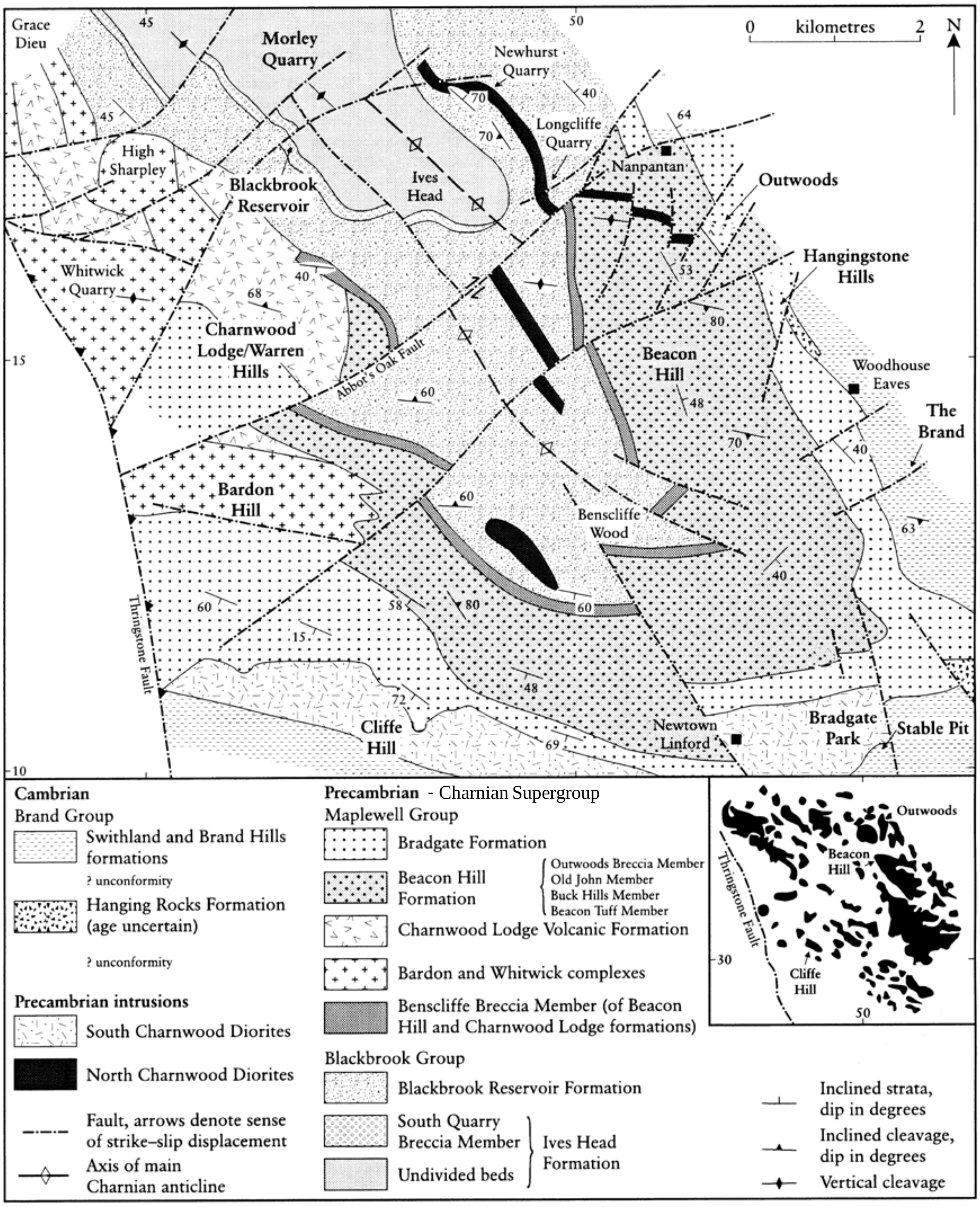


Figure 1 Geology of Charnwood Forest, showing the location of Bradgate Park. Inset at lower right shows actual outcrops of Precambrian and Cambrian rocks (black), separated by Triassic 'cover' strata (from Carney, 1999)

Key to units:
MM: Mercia Mudstone
SF: Swithland Formation
SP: Stable Pit Member
SD: South Charnwood Diorites
H: Hanging Rocks Formation
Bd: Bradgate Formation:
SB: Sliding Stone Slump Breccia
BH: Beacon Hill Formation

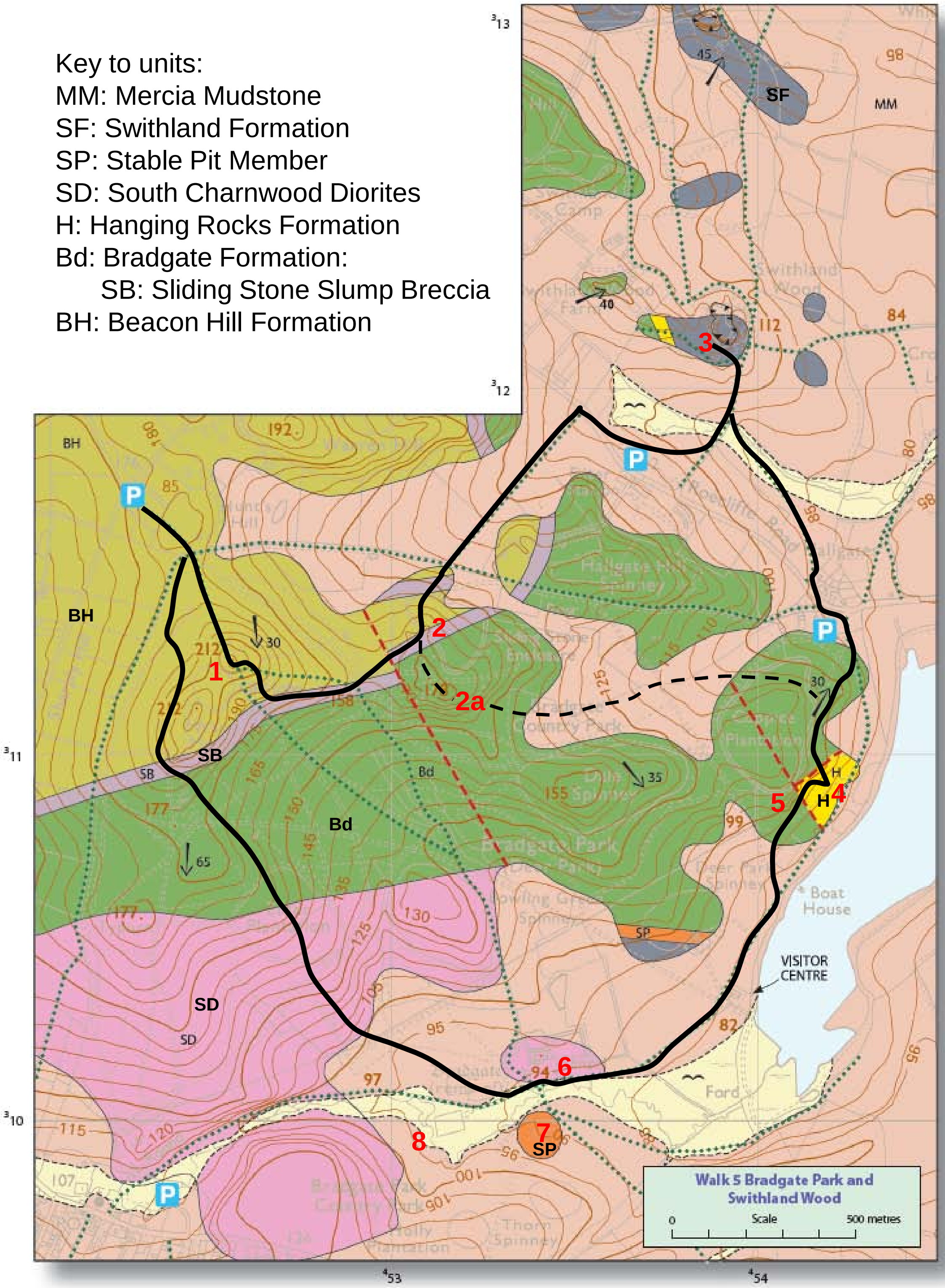


Figure 2 Geology of Bradgate Park, showing route of excursion (in black, with optional route shown as dashed line). Localities (red numbers) are described in the text. From Ambrose et al., 2007. OS topography © Crown Copyright. All rights reserved. BGS 100017897/2010"

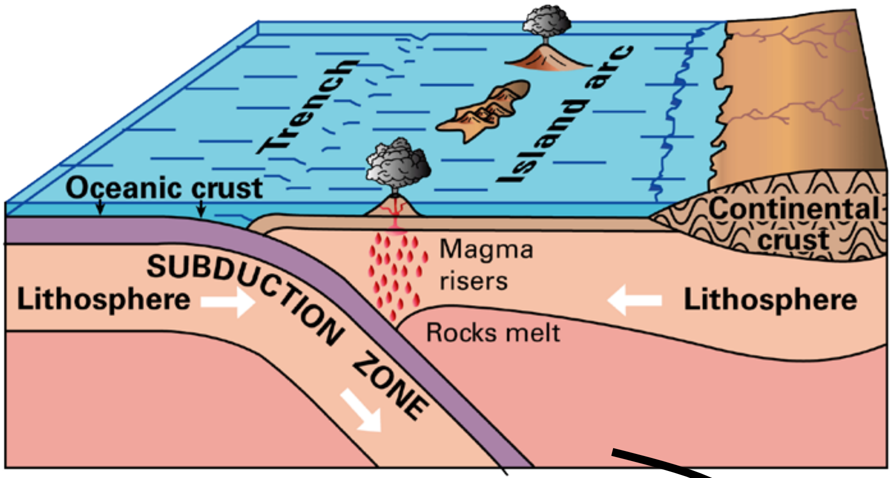
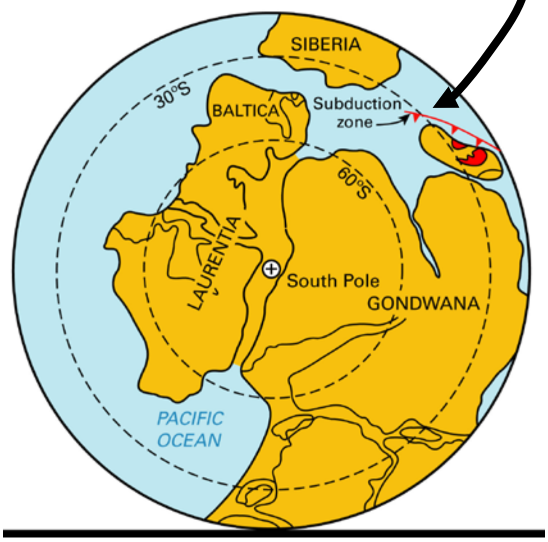


Figure 3 Subduction zone with volcanic arc – a model for Charnian magma generation

Figure 4a Position of England and Wales about 560 million years ago, when the Charnwood volcanoes were active



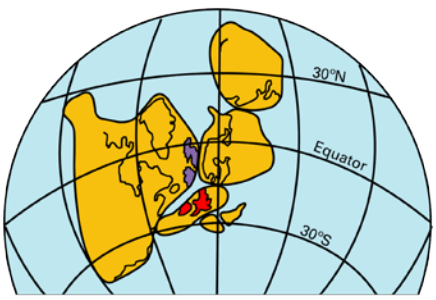


Figure 4b Configuration about 420 million years ago, immediately before the 'plate tectonic unification' of England and Scotland. Deformation at this time formed the Charnwood anticline and cleavage

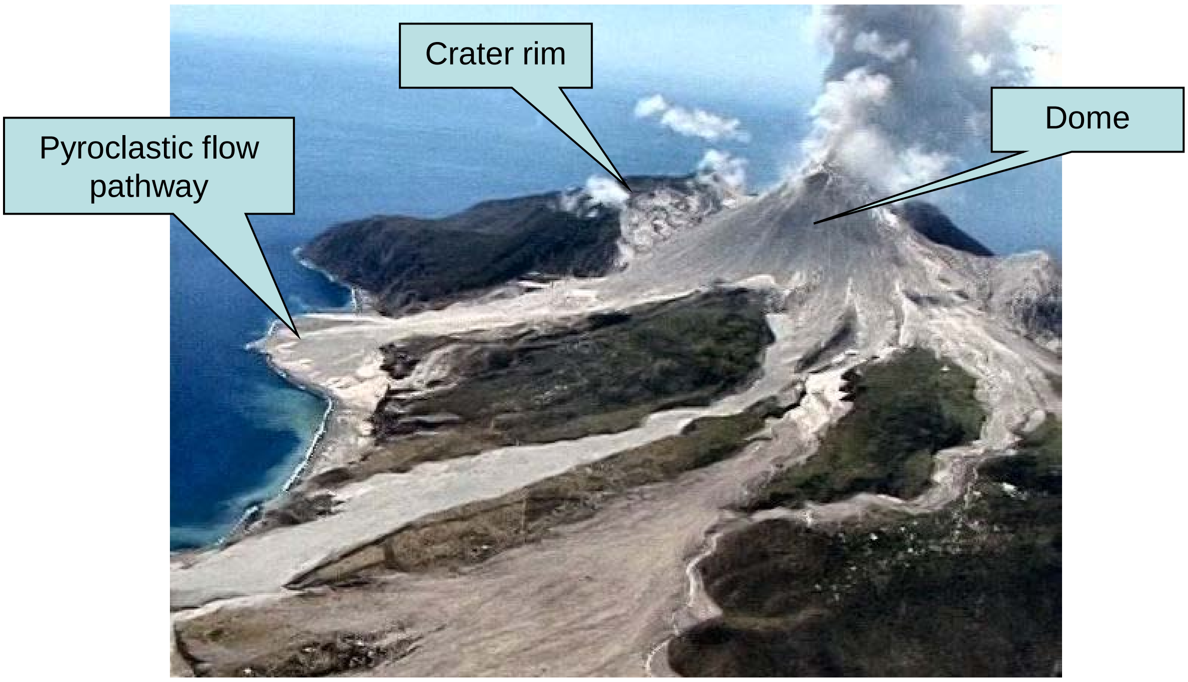
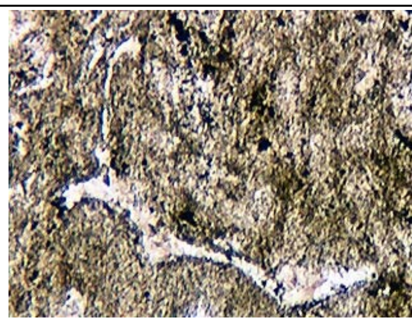


Figure 5. The Soufriere Hills volcano, Montserrat, c. 1997, showing summit crater, volcanic dome and pathway followed by pyroclastic flows – an analogy for Charnian volcanism

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



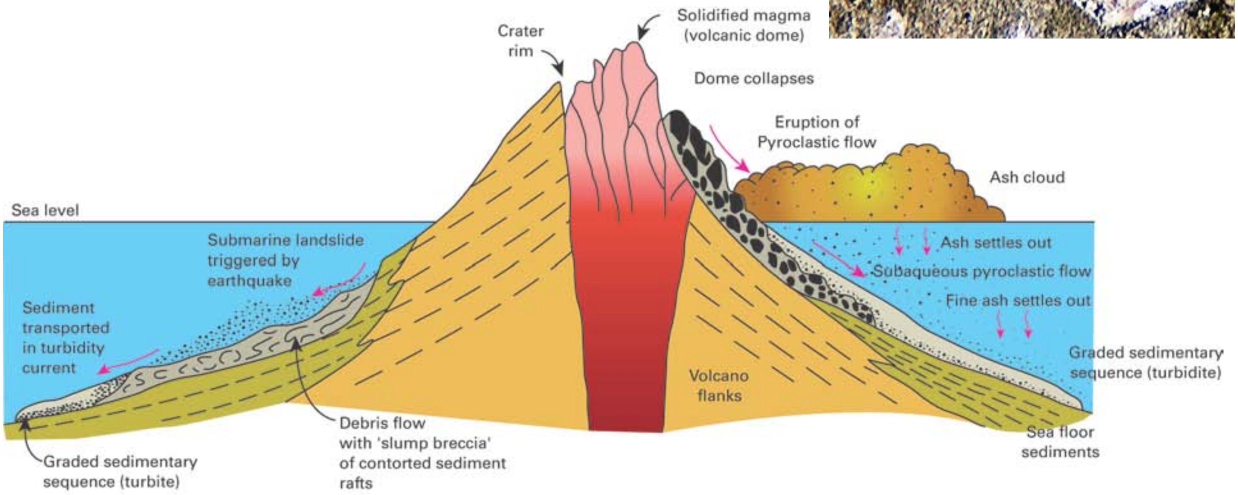


Figure 6. Cross-section through a Charnian volcano, based on the 'Montserrat' model (from Ambrose et al., 2007)

Figure 7 Principal features of the 'sag' structure above the Sliding Stone Slump Breccia (loc. 2):

Red dashed lines: upper and lower limits of syn-sedimentary deformation
Yellow solid lines: primary syn-sedimentary microfaults
Yellow dashed lines: peripheral brittle fractures
Note also, disturbances in the muddy layer below the coin

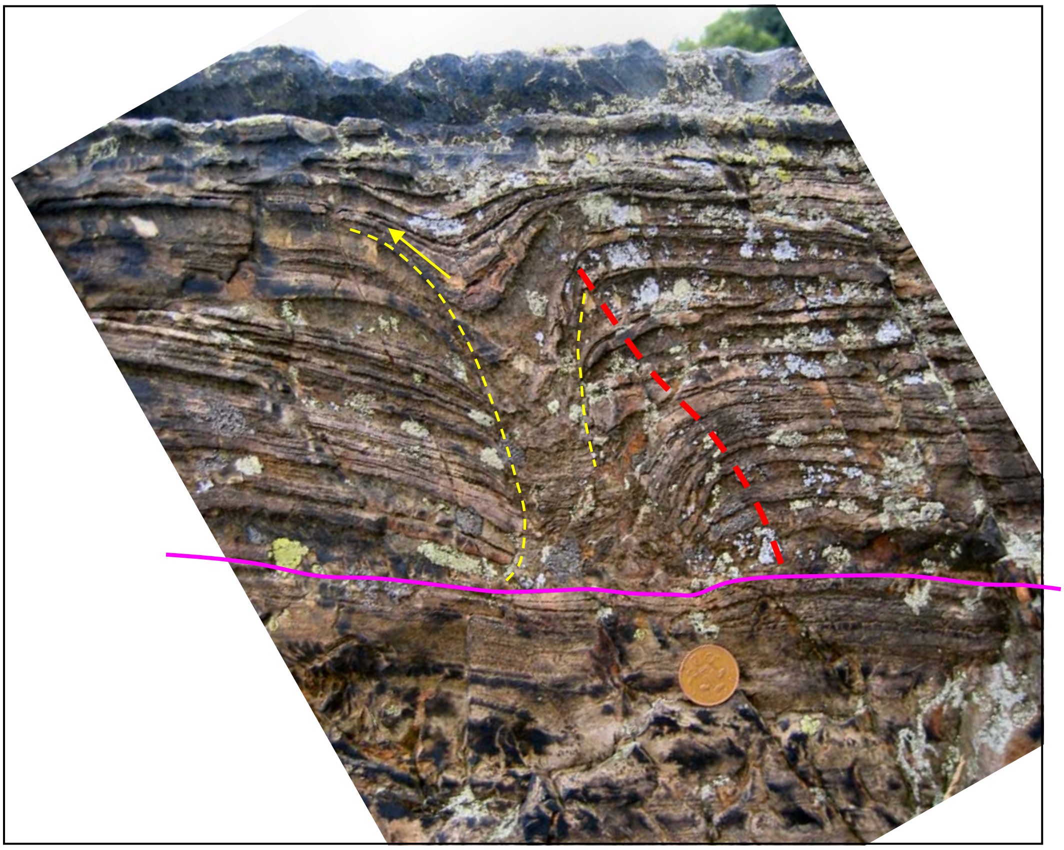
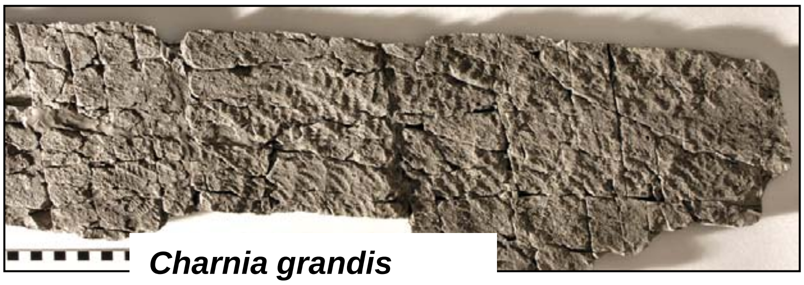
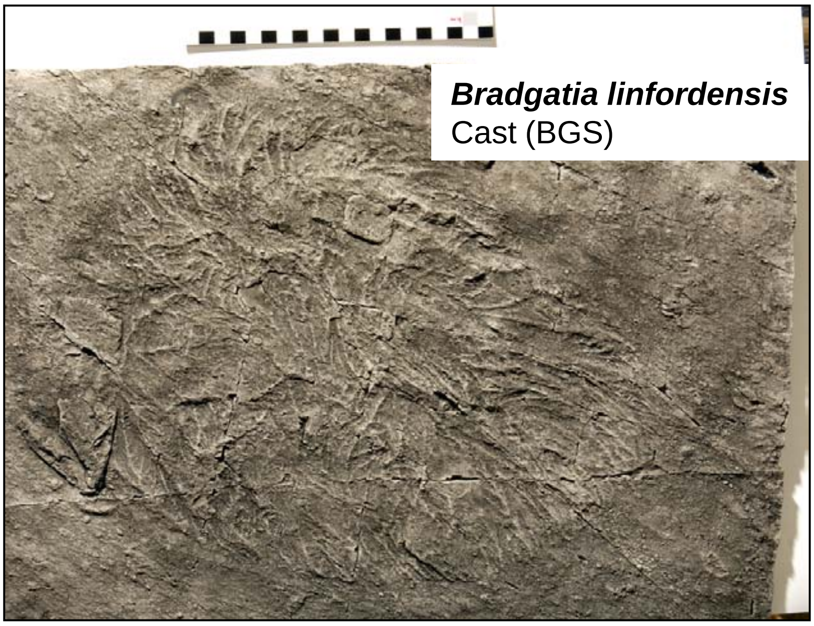


Figure 8 Structural synthesis of the 'sag' (see Figure 8), after restoration of the strata to their original horizontal attitude. Compression from right to left resulted in en-masse movement of a semi-lithified sediment package above a zone of decollement (purple line) just above the thin sandstone layer. It resulted in a syn-sedimentary asymmetric flexure (axis marked by red dashed line), and the 'sag', which is defined by zones of microfaulting (yellow dashed lines). The left-hand fault zone shows reverse movement in part, indicated by the yellow arrow. Note that the 4-5 beds at the top appear to thicken into the sag structure, but are not disrupted by the microfaults.

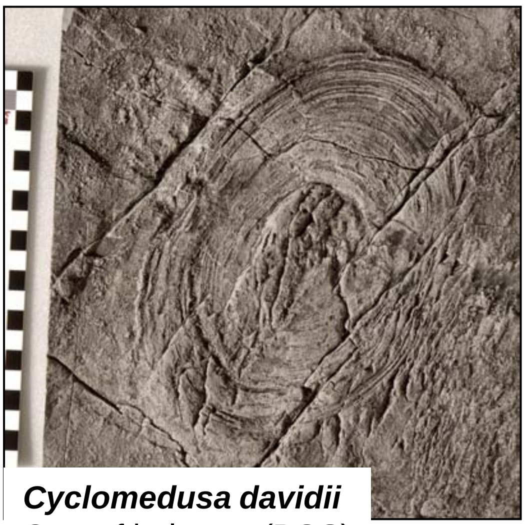


Charnia grandis
Cast of holotype (BGS)

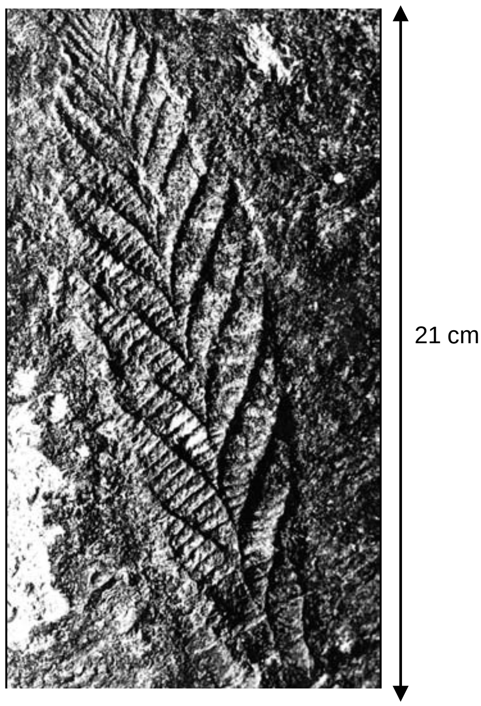
Charniodiscus concentricus
Cast of holotype in Leicester Museum



Bradgatia linfordensis
Cast (BGS)



Cyclomedusa davidii
Cast of holotype (BGS)



Charnia masoni
Holotype in Leicester Museum

Figure 9. Selected Precambrian fossils from various localities in Charnwood Forest