Precambrian Rocks of England and Wales

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Chapter 2

Charnwood Forest

INTRODUCTION

J. N. Carney

The scattered Precambrian inliers of Charnwood Forest together constitute one of the larger basement occurrences in England. The simple structure, involving broad anticlinal folding of the sequence, has brought to crop about 3.5 km of strata and revealed what is arguably one of the most extensive and continuous sequences through a subaqueous volcaniclastic succession to be found anywhere in Britain. Although this region has long been a classic area for Precambrian geology, its importance for regional stratigraphical studies has been underlined by recent advances showing that part of the succession may be Cambrian in age.

Previous workers recognized that the complex Precambrian outcrop patterns (Figure 2.1, inset) are due to the partial exhumation of a buried mountainous topography dating to early Triassic times (Watts, 1903; Bosworth, 1912). This process has contributed to the distinctive modern landscape of Charnwood Forest and produced many spectacular sections through the Precambrian–Triassic unconformity in quarries, but its unfortunate legacy is that natural Precambrian rock exposure has been restricted to small craggy knolls. Despite these problems, and a widespread Quaternary cover, geological mapping over the years (e.g. Watts, 1947; Moseley, 1979; Worssam and Old, 1988; Carney, 1994) has resulted in a detailed subdivision of the Precambrian rocks and structures affecting them, as portrayed in Figure 2.1.

Publications on the basement rocks of Charnwood Forest extend back over two centuries, and the region has long been important to the development of many scientific issues related to English basement geology and the recognition of ancient volcanic sequences, as summarized by Watts (1947) and Ford (1979). The culmination of this research is a stratigraphical hierarchy formalized by Moseley (1979) and Moseley and Ford (1985). In their scheme the bedded volcaniclastic rocks are collectively termed the Charnian Supergroup and this in turn is subdivided into the major groupings shown in Figure 2.1.

The eight stratigraphical GCR sites, featured in Figure 2.1, are chosen to represent as much of the Charnian succession as possible, and to show the wide variety of lithologies and environments involved in its evolution. It should be noted that the Brand Group, at the top of the sequence, is now considered to be at least in part Lower Cambrian. Consequently the GCR sites that mainly portray it (Stable Pit and 'The Brand') have been placed within a separate chapter (9) devoted to rocks of probable Lower Palaeozoic age. One of the outstanding features contributing to the international geological importance of Charnwood Forest is the preservation on bedding planes of Precambrian fossil impressions; six palaeontological localities have been discovered, and are described in Chapter 8.

Clues to the ultimate origin of the magmas that built up the Charnian sequence are provided by major and trace element geochemical data for the Charnian Supergroup and its associated volcanic complexes, as summarized by Pharaoh *et al.* (1987b). The rocks are characterized by high contents of Large Ion Lithophile (LIL) trace elements (e.g. K, Rb and Ba) combined with High Field Strength (HFS) element abundances (e.g. Zr, Hf, Y and Yb) that are well below values for mid-ocean-ridge basalt (MORB). They therefore have calc-alkaline attributes, as previously recognized by Thorpe (1974) and Le Bas (1982), which in turn indicates that the parental magmas were of volcanic arc type, generated in a subduction zone setting. Similar values for the HFS elements characterize magmas supplying modern volcanic arcs of very primitive type, suggesting that the Charnian Supergroup was originally founded upon oceanic crust or highly attenuated continental crust.

Cessation of Charnian volcanism was followed by two intrusive episodes. The first of these involved the emplacement of the North Charnwood Diorites and the second and final phase, the South Charnwood Diorites (terminology of Worssam and Old, 1988). The former intrusions are geochemically indistinguishable from the extrusive Charnian rocks, although they are generally of more basic composition. By contrast, the South Charnwood Diorites, locally known as 'markfieldite', are distinctive on account of their granophyric textures and geochemistry. Pharaoh *et al.* (1987b) note that in comparison with the earlier Charnian rocks, the South Charnwood Diorites are highly enriched in LIL elements, particularly K, plus Ce and P. However, Nb, Ta and other HFS elements remain below MORB values except in the most evolved samples. Such features indicate that the diorite magmas belong to the high-K calc-alkaline series

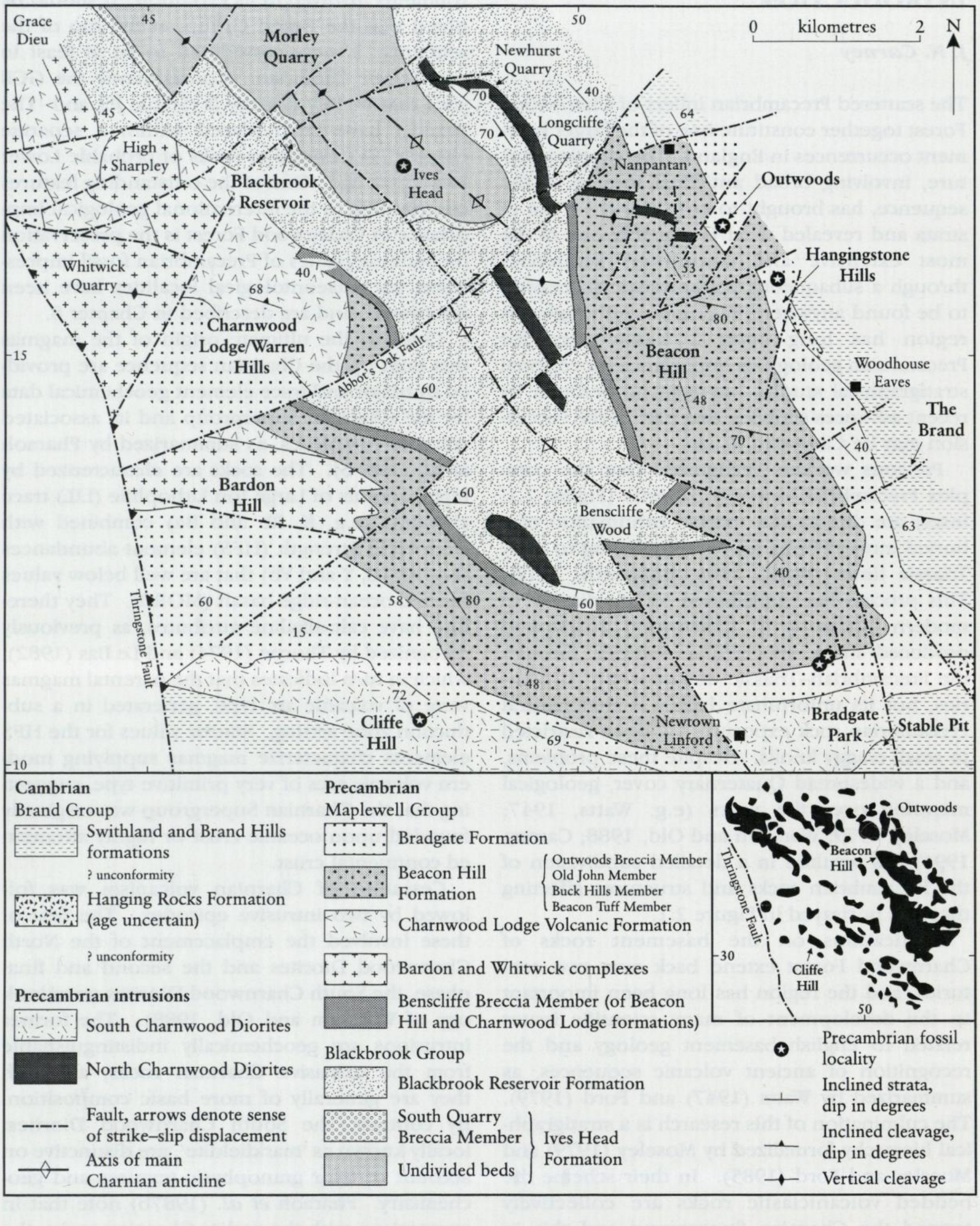

Figure 2.1 Geological map of Precambrian and Cambrian rocks in Charnwood Forest, showing the locations of the GCR sites (in bold lettering). Note that younger rocks are omitted for clarity. The inset shows the actual extent of the 'basement' inliers (dark shading) between this younger cover. The latter mainly consists of Triassic strata, with Coal Measures included to the west of the Thringstone Fault; extensive veneers of Quaternary drift are also present (modified from Worssam and Old, 1988).

and were emplaced at a time when the Charnian arc had achieved greater maturity and was floored by thickened crust (Pharaoh *et al.*, 1987b).

The distinctive geochemical signature of the Charnwood basement rocks is one of the principal reasons for equating them with the Precambrian occurrences of the Nuneaton inlier, described in Chapter 3 (Carney and Pharaoh, 1993; Bridge *et al.*, 1998). The relevant geochemical comparisons that can be drawn between the two occurrences have considerable implications for regional geology. They extend the distribution of 'Charnian' type rocks for at least 20 km to the south-west, and support the hypothesis of a 'Charnwood Terrane' (Chapter 1), whose distribution is shown in Figure 1.1. This forms one element of the collage of diverse volcanic and metamorphic terranes that comprises the Precambrian basement of England and Wales (see Chapter 1).

Chemical comparisons that have been made between the South Charnwood Diorites and the granophyric diorite intrusion exposed at the Judkins' Quarry GCR site, Nuneaton (Chapter 3), are especially significant to the age of Charnian magmatism since they are supported by $\epsilon Nd(t)$ isotope evidence that the Nuneaton granophyric diorite and South Charnwood Diorites were both generated at the same point in time (McIlroy *et al.*, 1998). This is a critical observation because the Nuneaton granophyric diorite, with a U-Pb age of 603 ± 2 Ma (Tucker and Pharaoh, 1991) is the only outcropping Precambrian rock that has been precisely dated in this part of England.

Direct radiometric age determinations have been conducted on Charnwood Forest rocks but the techniques so far used have yielded ambiguous results (see reviews in Worssam and Old, 1988; Moseley and Ford, 1985; Sutherland *et al.*, 1994). A suite of K-Ar determinations (Meneisy and Miller, 1963) has given values ranging widely between 684 ± 29 and 260 ± 15 Ma, which must in part reflect the complex Palaeozoic deformational history of this region. A late Neoproterozoic Rb-Sr age of 552 Ma was obtained on a sample from the South Charnwood Diorites, but had a large error range of $\pm$ 58 Ma rendering the result uninterpretable (Cribb, 1975). Other criteria normally regarded as reliable for determining age are currently controversial. For example, the Charnian Precambrian fossil assemblage has been equated with Ediacara-type faunas that in other parts of the world are considered to be no older than 580 Ma (e.g. Bowring *et al.*, 1993; McIlroy *et al.*, 1998). At the Cliffe Hill GCR site, fossil-bearing Charnian strata are intruded by the South Charnwood Diorites, but if these intrusions are indeed equivalents of the Nuneaton granophyric diorite (see above) the latter's radiometric age would make the Charnian faunas older than the Ediacaran by at least 20 million years.

Within the Caledonide orogenic belt to the north-east of Charnwood Forest, concealed Precambrian volcanic rocks were proved in the Orton and Glinton boreholes, between Leicestershire and Norfolk. These rocks were dated by the U-Pb method at 612 and 616 Ma by Noble *et al.* (1993, and Figure 1.2). Their chemical compositions suggest they may not be precise equivalents of the Charnian Supergroup, but may instead constitute part of a separate Precambrian volcanic arc system, the Fenland Terrane shown in Figure 1.1, to the east of the Charnwood Terrane.

An episode of Precambrian folding has been detected at the Cliffe Hill Quarry GCR site, intervening between deposition of the Charnian Supergroup and intrusion of the South Charnwood Diorites. An entirely unrelated deformation was responsible for the anticlinal structure of the Charnian Supergroup (Figure 2.1) and the penetrative cleavage that affects it. This cleavage is steeply dipping, with NW–SE to WNW–ESE orientations, and is an essential fabric element accentuated in the finer-grained rocks of the Charnian Supergroup but also present in many of the massive pyroclastic rocks and intrusions. The possibility that this cleavage is structurally related to the main Charnian anticline has been hotly debated in the past. Watts (1947) believed that the cleavage was Precambrian (Neoproterozoic), although formed after the anticlinal fold. On the other hand, Jones (1927) suggested a Caledonian age for the cleavage, implying that it was not related to Charnian folding. Evans (1963) disagreed, observing that even though the cleavage apparently cuts across the main Charnian fold axis, this did not rule out contemporaneity between the two types of structure. Nowadays such a relationship is referred to as cleavage-fold transection, and is commonly observed in orogenic terranes where lateral movements have accompanied compression (e.g. Soper *et al.*, 1987). The anticlockwise-transecting cleavage geometry of Charnwood

Forest was described in some detail by Moseley (1979) and has been recognized by measurements taken on outcrops at the Bradgate Park GCR site. To determine the cleavage age, tectonic mica fabrics were sampled from several exposures, including those at 'The Brand' GCR site, and analysed for their $^{40}Ar/^{39}Ar$ ratios. The results have been combined statistically to give an age indicating that the deformation occurred during the Acadian (Siluro-Devonian) orogenic event that affected much of the basement of central England (BGS, unpublished data).

The metamorphic grade of the cleavage-forming recrystallization event has been estimated from XRD techniques used to determine the Kubler indices of white mica (illite) crystallinity; the values obtained, mainly grouped between 0.15 and 0.24, are indicative of epizonal (greenschist facies) metamorphic conditions (Merriman and Kemp, 1997). In thin sections of finer-grained rocks, this fabric consists of well-crystallized, oriented intergrowths of white mica and chlorite that are largely of tectonic origin. Because of this metamorphism, most Charnian lithologies should be prefixed with the term 'meta'. To prevent tiresome repetition of the same letter strings, however, this practice will not be followed here.

Charnian Supergroup

The Charnian Supergroup currently includes the three main groupings established by Moseley and Ford (1985), as shown in Figure 2.1. However, the Precambrian affinity of the youngest division, the Brand Group, is now doubted and it may possibly be Lower Cambrian in age (Bland, 1994; Bland and Goldring, 1995). The ramifications for Charnian stratigraphy are that parts of the Brand Group, perhaps even the whole of this division, may eventually be excluded from the Charnian Supergroup, if this term is to be restricted only to the Precambrian part of the sequence. In this volume, two of the former Charnwood GCR sites (Stable Pit and Brand Hills), now possibly containing Lower Cambrian rocks, are described in a separate chapter (9). Their stratigraphical context is discussed further in the *British Cambrian to Ordovician Stratigraphy* GCR volume (Rushton *et al.*, 1999).

The mode of formation of the Charnian rocks, and their tectonic setting, can be partly deduced from their geochemical attributes, which have already been summarized. These show that the parental magmas were calc-alkaline and similar to those of modern evolved volcanic arcs founded upon oceanic or attenuated continental crust. Many modern intra-oceanic arc systems are largely submerged, and consequently it is the fragmental material, either eroded or ejected from the volcanic axis, that is the most likely to be preserved in the depositional basins that surround the arc. This explains why the Charnian Supergroup is mainly composed of well-stratified volcaniclastic lithologies (terminology of Fisher and Schmincke, 1984; see Table 1 in the Glossary, in the present volume), as exemplified, for example, at the Morley Quarry, Outwoods–Hangingstone Hills and Bradgate Park GCR sites. Such strata contain varying proportions of epiclastic material (derived from erosion) and pyroclastic constituents (derived directly from volcanic eruptions), with an important pyroclastic component in the Maplewell Group (Moseley and Ford, 1989), particularly the Beacon Hill Formation exposed at the Beacon Hill GCR site. The Beacon Hill Formation is replaced to the north-west by the Charnwood Lodge Volcanic Formation (Figure 2.1); that unit is dominated by coarse-grained, block-rich lithologies, seen at the Warren Hills and Charnwood Lodge GCR site, and is interpreted as part of a volcaniclastic apron to local volcanic centres (Carney, 2000). Magmatic source regions in this north western part of the Charnian Supergroup are represented by lithologies interpreted as shallow-level intrusions occurring in close proximity to the Charnwood Lodge Formation. These assemblages cannot be subdivided lithostratigraphically and are known as the Bardon and Whitwick volcanic complexes (Moseley and Ford, 1985; Carney, 1999), the former exposed at the Bardon Hill GCR site.

The volcaniclastic beds of the Charnian Supergroup show a general absence of well-organized sedimentary structures, such as cross-bedding, which may be indicative of tidal reworking at shallow depths. Wave ripples, tentatively identified only at the Beacon Hill GCR site, could nevertheless suggest rare episodes of shoaling to depths above those appropriate to the limit of wave influence (i.e. above storm-wave base). It is further possible that some of the parallel-laminated sandy strata were storm-deposited, again suggesting the possiblity of a nearshore influence. On the other hand, relatively deep-water, offshore environments are more in keeping with sedimentary structures such as grading, slump-folding and various other types of soft-sediment deformation. These features suggest deposition from debris flows, pyroclastic flows and turbidity currents triggered by instability on the more distant, and shallower, flanks of basins marginal to the active volcanoes. In such environments the Charnian Ediacaran fauna evidently thrived and was at times preserved on the bedding planes of the finer-grained lithologies (Chapter 8).

North and South Charnwood Diorites

Two suites of intrusions (Figure 2.1), distinct from each other in petrography and chemistry, represent the final Charnian magmatic phases. The North Charnwood Diorites form sub-vertical sheets up to 60 m thick consisting of medium- to coarse-grained diorite with subordinately developed granophyric textures. They are not represented at any of the GCR sites, but are geochemically equivalent to the narrower and finer-grained sheets of basaltic-andesite described in Boon's and Judkins' quarries at Nuneaton (Bridge *et al.*, 1998).

The coarser-grained, granophyric-textured diorites of southern Charnwood Forest were termed 'markfieldite' by Hatch (1909) but Wills and Shotton (1934) preferred 'granophyric diorite' as the more accurate name. Nowadays they are placed within a 'South Charnwood Diorite' association of intrusions, which are more leucocratic, contain visible quartz, and are less sheared than the North Charnwood Diorites (Worssam and Old, 1988). The South Charnwood Diorites represent the youngest magmatic phase and, as discussed above, they are geochemically comparable to the granophyric diorite at Nuneaton that has been dated at 603 ± 2 Ma. It has commonly been assumed that these intrusions were emplaced into all parts of the Charnian Supergroup. However, the youngest definite intrusive contacts are against strata equated with the Bradgate Formation of the Maplewell Group, as described at the Cliffe Hill Quarry GCR site. The South Charnwood Diorites have not been proved to cut the stratigraphically highest beds of the Charnian Supergroup, and as noted by McIlroy *et al.* (1998), the Brand Group strata contain granophyre pebbles that are geochemically and petrographically identical to the South Charnwood Diorites (see Chapter 9). Erosional unroofing of these intrusions prior to deposition of the Brand Hills and Swithland formations would be compatible with the Lower Cambrian age recently proposed for those units.

MORLEY QUARRY (SK 4765 1785)
POTENTIAL GCR SITE

J. N. Carney

Introduction

The selection of Morley Quarry as a GCR site is justified by accessibility (Figure 2.2), local conservation status, and the fact that it displays strata belonging to the oldest exposed Charnian unit, the Ives Head Formation, which is a component of the Blackbrook Group (Figure 2.1). The type section for the Ives Head Formation is on the summit of Ives Head, about 850 m to the south (Moseley and Ford, 1985), and it is there that the oldest fossil-like impressions are found (Chapter 8). Morley Quarry contains a diverse volcaniclastic succession of some 40 m thickness, which is very similar to that of the type section and thus furnishes an important reference section for the Ives Head Formation (Carney, 1994).

An added dimension to this site is provided by the findings of research drilling carried out in the quarry by the BGS as part of an investigation into the geothermal potential of the UK. The borehole section, described by Pharaoh and Evans (1987), encountered a further 541 m (apparent thickness) of strata belonging to the Ives Head Formation and then entered a sequence consisting mainly of massive, grey, feldspar-phyric dacite, interpreted as lava flows. This lower unit extends between 541 m and the base of the borehole at 835.5 m; named the Morley Lane Volcanic Formation by Carney (1994), it is nowhere exposed in Charnwood Forest.

This site also offers excellent conserved exposures of an extremely sharp unconformity surface developed upon the Precambrian rocks where overlain by Triassic strata of the Mercia Mudstone Group.

Description

The succession on the eastern quarry face (Figure 2.3) represents the upwards continua-

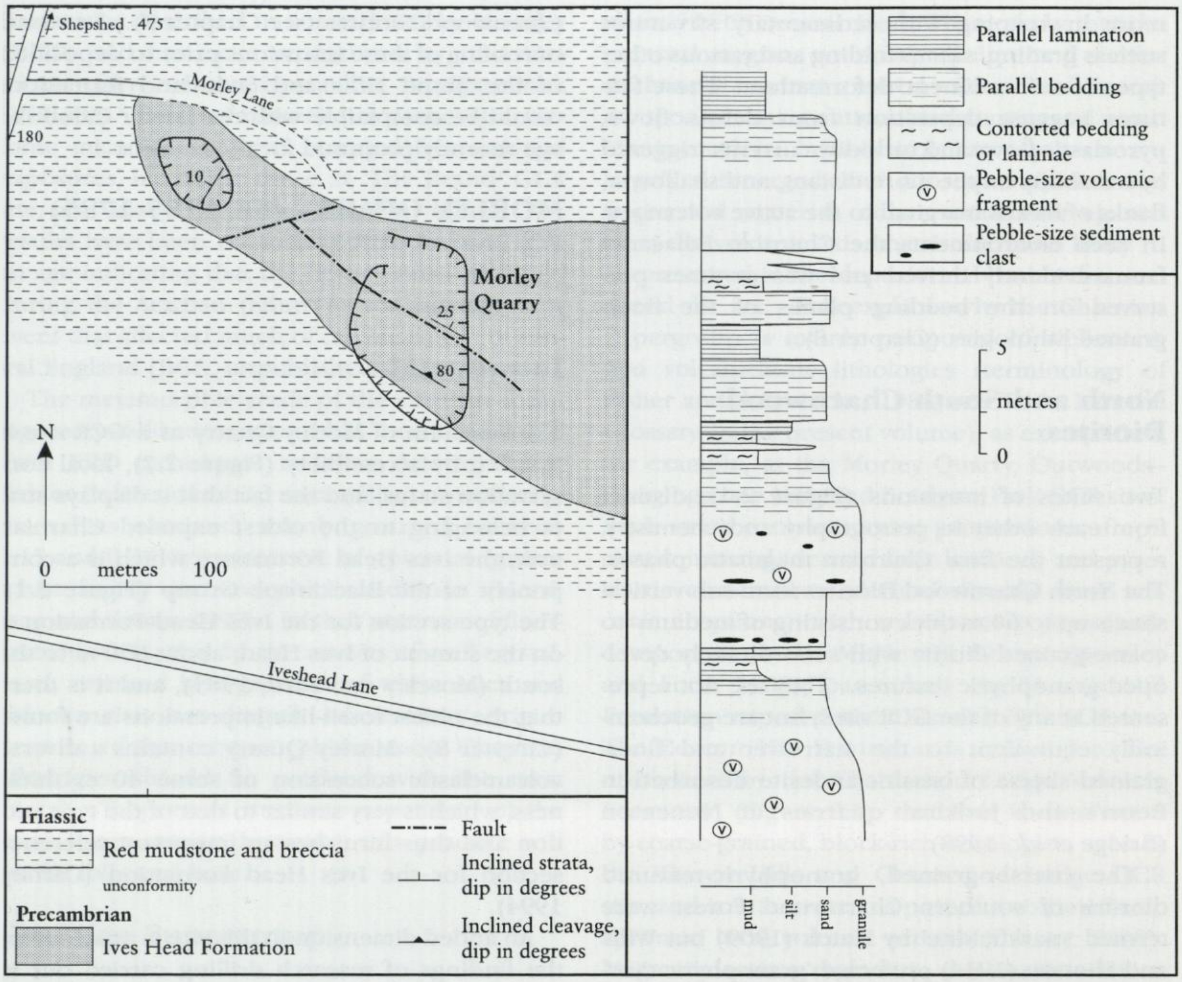

Figure 2.2 Geological map of the Morley Quarry site. Column at right is based on a measured section of the beds exposed on the eastern face of the quarry (Carney, 1994).

tion of the strata cored in the Morley Quarry Borehole. The fine-grained lithologies are variegated in the dark grey and grey-green colours typical of the Blackbrook Group. They comprise packages, up to 3 m thick, of volcaniclastic mudstone and siltstone displaying millimetre- to centimetre-scale parallel-stratification. Other features include repetitive normal grading, shown by successions with beds consisting of fine-grained sandstone passing up to silty or muddy tops with convoluted or wispy lamination.

The lower part of the Morley Quarry succession contains beds up to several metres thick (Figure 2.2) which are graded from bases composed of massive, very coarse-grained to granule-grade volcaniclastic sandstone with sporadic, subangular, volcanic and sedimentary clasts up to 30 mm across. The grading generally becomes apparent a few metres upwards and is revealed by a gradual increase in the degree of sorting, a corresponding slight decrease in grain size and the development of a diffuse, parallel stratification. The graded cycles culminate in laminated mudstones and siltstones, although these may rest sharply on the underlying stratified volcaniclastic sandstone component. In thin sections, the matrix of the coarse-grained lower parts of the graded beds contains abundant irregular-shaped grains and granules composed of fine-grained 'felsitic' volcanic lithologies, some glassy with relict spherulitic textures and many with small quartz and plagioclase phenocrysts. The same crystals also occur in isolation, forming the larger part of the matrix.

The NNE dip of strata in the quarry contrasts with the westerly dip in the smaller quarry far-

Figure 2.3 Well-bedded to laminated volcaniclastic strata of the Ives Head Formation exposed on the eastern face of Morley Quarry. (Photo: J.N. Carney.)

ther west (Figure 2.2); a complex local structural situation is suggested, perhaps due to flexuring and/or faulting. The ubiquitous Charnian cleavage is seen here as a faint, millimetre-spaced, WNW-trending penetrative foliation. On the western quarry face, however, the cleavage is accentuated and shows crenulation both within and adjacent to a NW–SE trending complex of faults, indicative of a second, non-penetrative phase of deformation.

Details of the Triassic unconformity are magnificently displayed along the southern quarry face. The Charnian rocks are unweathered beneath the unconformity, which shows sharp, step-like irregularities indicating that erosion had preferentially picked out sub-vertical joints in the Precambrian basement. The Triassic strata pinch out in the direction of Morley Hill, through which the eastern quarry face is excavated, indicating that this hill represented an important local feature of the Triassic palaeotopography. The lowermost Triassic beds consist of a *c.* 1–2 m-thick breccia of angular Charnian fragments within a red, silty sandstone matrix. The high matrix content suggests these beds are mainly accumulations of finer-grained material derived from weathering ('sanding') processes, with a relatively small input from talus aprons (angular fragments) that mantled the Triassic forerunner to Morley Hill.

Interpretation

The Morley Quarry exposures illustrate well the processes of sedimentation within the Ives Head Formation. Normal grading and convoluted lamination are indicative of rapid subaqueous deposition, whereas the general absence of cross-bedding suggests there was little influence from wave or current action and therefore moderate to deep water environments of accumulation. The graded volcaniclastic sandstone beds are interpreted as the deposits of proximal-facies turbidites (e.g. Walker, 1967), representing sediment gravity flows in which grains were suspended by turbulence. Such flows were possibly initiated by instability within unconsolidated sediments previously deposited along the basin margin, but may also represent the distal, subaqueous continuations of volcaniclastic debris flows (Fisher, 1984), or even pyroclastic flows. There is little evidence to show their true origins, however, since all of the textures and fabrics seen here are the result of depositional processes. The structureless lower parts of the graded beds correspond to the suspension-sedimentation stage of deposition in high-density turbidites, when sediment fall-out was occurring at a high rate and there was no time to form structures such as bedding. The upper, parallel-stratified facies of the beds indicates a greater degree of sedimentary 'organization' and represents the traction-sedimentation stage, when flowage of the sediment became less steady and grains settled out progressively on deposition, forming a series of parallel beds (Lowe, 1982).

The finer-grained beds capping many graded cycles, and also predominating higher in the quarry sequence, either represent the more distal, low-density deposits of subaqueous debris flows, or material that was mobilized directly from finer-grained accumulations when the Charnian volcanic arc was quiescent. Not all such beds are graded, but in overall lithology they are similar to the sand–mud couplet facies that Ghibaudo (1992) attributed to various Bouma-type turbidite sequences.

Conclusions

Morley Quarry offers highly accessible exposures of the oldest Precambrian volcaniclastic rocks in Charnwood Forest. The sedimentary structures that are well displayed indicate that the Ives Head Formation was deposited from turbidity currents, which are essentially subaqueous turbulent flows of sediment grains. The thickest turbidite beds are characterized by normal grading, being extremely coarse-grained in their basal parts and fining upwards, with increasing degrees of stratification, to laminated sandy or silty tops. The dominant grain constituents are crystals and fragments of fine-grained volcanic rock, suggesting that the turbidite flows were in some way triggered by volcanic eruption. However, the extent of sedimentary reworking during turbulent flowage has masked any evidence for primary volcanic processes and has produced lithologies that are best described as 'volcaniclastic' rather than 'pyroclastic' in nature (see Table 1 of Glossary). The site contains structures indicating that the Charnian cleavage was folded and disrupted by subsequent faulting. It also contains excellent exposures of the unconformity separating Precambrian rocks from overlying Triassic strata.

BLACKBROOK RESERVOIR (SK 464 171)

J. N. Carney

Introduction

This site is of considerable stratigraphical importance since it contains the type section for the South Quarry Breccia Member (Moseley and Ford, 1985). This is a prominent and easily mappable marker horizon, whose top surface coincides with that of the Ives Head Formation (Figure 2.1). It is also an excellent example of one of the particularly coarse-grained units that punctuate the Charnian sequence. The exposures show that the breccia component is confined to a 2–3 m-thick layer just above the base of this *c.* 35 m-thick unit. The site also includes exposures of coarse-grained strata at the base of

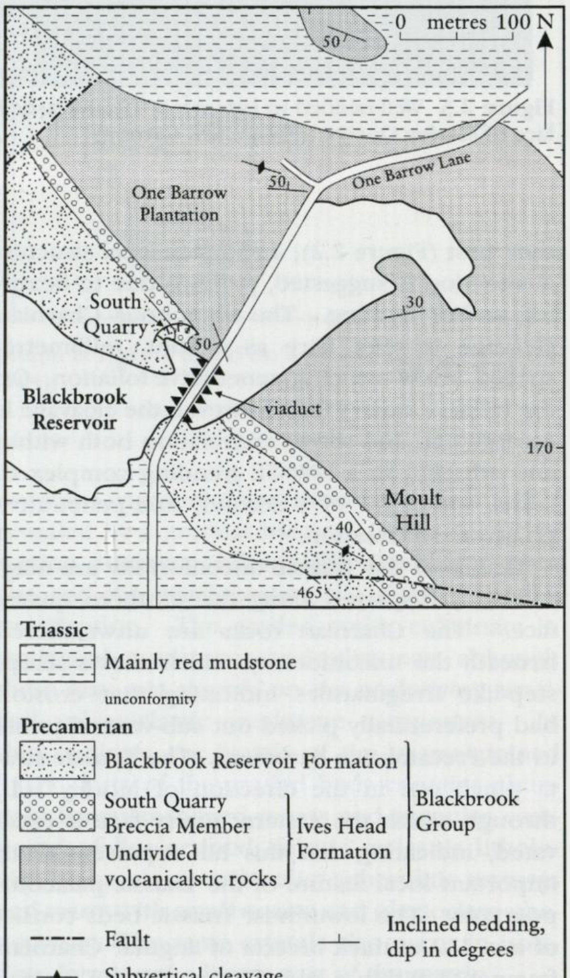

Figure 2.4 Geological map of the Blackbrook Reservoir site.

the South Quarry Breccia Member, and finely laminated beds of the Ives Head Formation, just below (Figure 2.4).

Description

The best section, at the northern end of the viaduct across Blackbrook Reservoir, commences in strata forming an exceptionally well-laminated sequence of pale grey to pale green volcaniclastic mudstones and siltstones. Minor soft-sediment disruption is indicated by gently wavy lamination and low-angle truncations between laminae sets. They are abruptly succeeded by the South Quarry Breccia, which commences in a few metres of stratified to massive, pink-weathering, medium- to coarse-grained volcaniclastic sandstone. The overlying breccia facies is a further few metres in thickness and is exposed at the summit of One Barrow Plantation. Its most striking feature are slivers and rafts, up to 1.5 m long, consisting of white-weathering, laminated volcaniclastic siltstone and mudstone showing gentle flexuring within the breccia matrix (Figure 2.5). This matrix is pale grey, coarse-grained and poorly sorted, with up to 60 per cent quartz and plagioclase crystals and with prominent small (3–16 mm-size) clasts of cream or black volcanic rocks. In thin sections, the more intact crystals show some euhedral faces and the lithic clasts, representing fragments of dacite or acid tuff, contain euhedral and commonly embayed quartz and plagioclase crystals enclosed within a fine-grained felsic

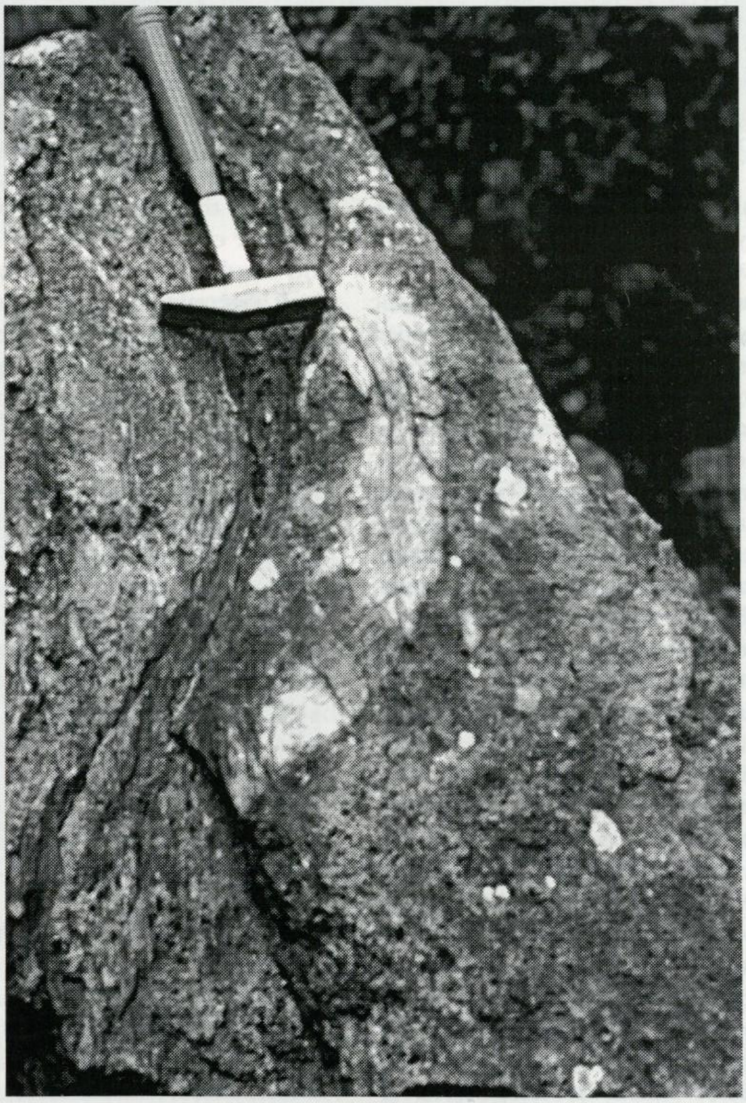

Figure 2.5 Siltstone clast in coarse-grained volcaniclastic sandstone of the South Quarry Breccia Member, Blackbrook Reservoir. (Photo: J.N. Carney.)

groundmass. The 29 m thickness of interbedded fine- and coarse-grained 'rhyodacitic tuffs' comprising the topmost part of the member (Moseley and Ford, 1985) are not exposed here, but are seen on Moult Hill, about 200 m along the strike to the south-east.

Further exposures of the Ives Head Formation in the lane to the NNE of the viaduct consist mainly of laminated volcaniclastic mudstones and siltstones with sporadic thin beds of medium- to coarse-grained sandstone showing sharp, loaded bases. Cross-lamination is present, one example suggesting a SSE current direction; laminae also show rafting and minor convolutions. This sequence prominently displays the highly penetrative Charnian cleavage, which is sub-vertical with an ESE (110–120°) strike. A second foliation is seen as widely spaced (5–15 mm) systems of tension fractures, which are commonly filled by quartz and/or haematite; they are sub-vertical and strike at 070–100°.

Interpretation

The South Quarry Breccia Member was interpreted (Moseley and Ford, 1989) as a slump breccia. It was attributed to an episode of powerful dacitic pyroclastic activity in the volcanic hinterland, suggested by the very coarse-grained crystal and lithic-rich nature of the breccia matrix. However, its final emplacement, they suggested, was due to the liquefaction and subsequent movement of water-saturated sediment, resulting in the rafting of previously deposited siltstone layers. There is little petrographical evidence for the presence of juvenile pyroclastic material (e.g. vitric shards) in the breccia matrix, and so the involvement of pyroclastic activity in forming the pre-slump sequence cannot be proved. As noted by Cas and Wright (1991), however, pyroclastic flows can lose 'fines' such as volcanic ash upon entry into water, leaving behind a deposit enriched in the denser (lithic and crystal) constituents. The sharpness with which the member succeeds the underlying distal turbidites is perhaps further evidence for a major volcanic or tectonic event that marked the passage from the Ives Head Formation into the overlying Blackbrook Reservoir Formation.

Conclusions

The Blackbrook Reservoir site offers easily accessible exposures in strata defining the top of the Ives Head Formation, and in particular it includes one of the classic occurrences of a typical intraformational breccia within the Charnian Supergroup. The 'slump' origin of the South Quarry Breccia Member is demonstrated by its content of laminated siltstone clasts and rafts, which prove that a pre-existing bedded sequence had been disrupted, and is indicative of a phase of gravitational instability within the Charnian sedimentary pile. Detailed examination of the breccia matrix may show whether or not the very coarse-grained constituents (crystals and volcanic fragments) were supplied directly from erupting volcanoes by pyroclastic flows operating prior to slumping.

BEACON HILL (SK 510 148)

J. N. Carney

Introduction

Beacon Hill is a local landmark and public viewpoint, with excellent exposures that collectively serve as the type section for the Beacon Tuff Member of the Beacon Hill Formation (Moseley and Ford, 1985). This member, about 740 m thick, occupies a significant stratigraphical position since it is in part contemporaneous with the Charnwood Lodge Volcanic Formation farther

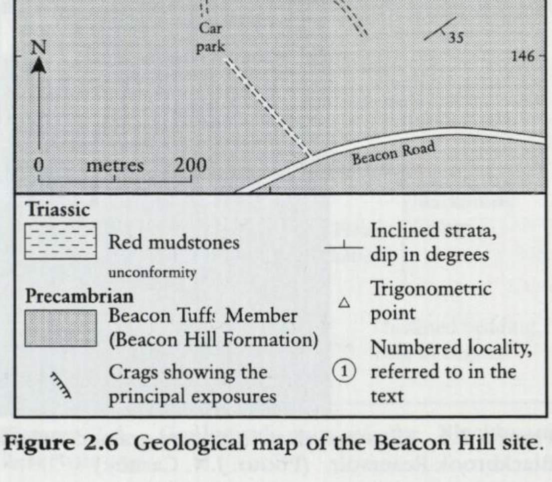

Figure 2.6 Geological map of the Beacon Hill site.

Figure 2.7 Exposure of fine-grained tuffaceous strata of the Beacon Tuffs Member, to the west of the trigonometric point at Beacon Hill. (Photo: J.N. Carney.)

north-west (Figure 2.1), which contains the principal record of primary pyroclastic activity in the Charnian Supergroup (Carney, 2000). Pyroclastic lithologies occur in the Beacon Tuff Member about 1 km north of Beacon Hill, forming about 180 m of very coarse-grained to lapilli-grade, massive dacitic tuff (Carney, 1994). At Beacon Hill the sequence is finer grained and the range of sedimentary structures suggests a considerable degree of secondary reworking. Accessibility of the exposures and the occurrence of well-polished rock surfaces are special features of the Beacon Hill site (Figure 2.6). They are important for demonstrating the relative significance of pyroclastic and epiclastic sedimentation processes during a period of raised volcanic activity in the Charnian arc.

Description

In the lower series of crags that form the base of the type section (Figure 2.6, Locality 1), about 6 m of these strata consist of white to grey, very fine-grained volcaniclastic rocks. These are mostly massive, but where bedding planes are seen they are in places highly irregular and convoluted; in one case, the contorted strata are truncated at the base of the overlying bed. Near the top of this section, parallel-laminated tuffaceous mudstones and siltstones show laminae disrupted into pencil-like rafts. Other laminae show evidence of incipient slumping in the presence of asymmetric drag-folds, whose direction of vergence is consistently towards the west.

The overlying beds, in the middle series of crags (Locality 2), consist of thinly bedded to parallel-laminated, tuffaceous siltstones with minor sandstones. An unusual occurrence, in the northern part of this exposure, consists of a 0.2 m-thick bed displaying what appear to be profiles through symmetrical ripples.

The youngest beds are exposed on the prominent crag by the footpath to the south-west of the trigonometric point (Locality 3); their eastwards dip, compared to the south-eastern dips of localities 1 and 2, outlines gentle synclinal folding of the Beacon Hill sequence at this site. In this predominantly fine-grained succession (Figure 2.7), the lowest bed, at least 2.8 m thick, consists of white-weathering, very fine-grained tuff or tuffaceous mudstone. It is devoid of bedding or lamination, similar to the basal tuffaceous rocks at Locality 1 (Figure 2.6), but careful examination of favourable surfaces shows a highly heterogeneous texture reminiscent of extensive intermixing between mud and silt-grade sediment. Spectacular sedimentary load structures characterize a prominent undulating bedding plane in the middle part of these crags, and are continued a few metres to the south where completely detached, ball-shaped masses of sediment are enclosed within a lower bed. The overlying bed responsible for the loading is 0.2 m thick and shows slight grading from tuffaceous siltstone at the base to a porcellanous, white-weathering mudstone at the top. The uppermost, laminated beds have highly lenticular geometries, due to a combination of large-scale slumping and intraformational scouring. The youngest exposed strata are best seen around and to the east of the trigonometric point; they are thinly bedded to laminated, with many examples of undulatory bedding, rafted or truncated lamination, normal grading and load structures.

Although Beacon Hill is not recognized as a major Precambrian fossil locality, the highest bedding planes surmounting the crags at Locality 3, west of the trigonometric point (Figure 2.6), nevertheless display one prominent discoid fossil characterized by a concentric internal structure. This fossil resembles a detached 'holdfast', or float, of the type discussed in Chapter 8.

Interpretation

The Beacon Hill exposures provide an opportunity to examine lithologies that are clearly of a distal facies with respect to the volcanic centres known to be active at that time in north-west Charnwood Forest (see the Charnwood Lodge GCR site report). Contemporary volcanism is strongly suggested by thin sections of these rocks, which show locally abundant juvenile pyroclastic material such as y-shaped glass shards (Moseley and Ford, 1985; see Figure 5.23 for typical examples). In such fine-grained lithologies it is commonly assumed that the unresolvable matrix surrounding the shards, and constituting most of the rock when seen in thin section, represents the highly comminuted, fine ash-grade equivalents of the shards, and that consequently the rock is a vitric tuff. As pointed out by Moseley and Ford (1989), however, the delicate textural details necessary to confirm such an origin were largely masked by subsequent devitrification of the glassy material. The resultant textures would in turn have been overprinted during consolidation of the sequence, producing the extremely hard, porcellanous character of these rocks, which have an unusually high silica content (79.81%; Moseley and Ford, 1989). The distinctive, very thick beds of fine-grained tuff in the sequence appear to be internally structureless, but it is possible that an earlier lamination may have been obliterated by liquefaction consequent upon large-scale movement within the sequence. Such a complex pre-diagenetic history is further suggested by undulatory and lenticular bedding, the extensive downward penetration of load structures, and incipient asymmetric slump folding of laminae. These features are also indicative of water-saturated conditions. Normal grading suggests the introduction of reworked pyroclastic material in low-density turbidity currents, but fine-scale lamination could also reflect a direct contribution by fall out during spells of waxing and waning pyroclastic activity in the volcanic source region(s). Turbidity currents generally imply moderately deep waters; however, the occurrence of symmetrical ripples, possibly indicative of oscillating wave action, may suggest that at times the depositional basin had shoaled to relatively shallower depths, above storm-wave base.

Conclusions

The Beacon Hill site exposes excellent examples of strata made up of material that has been ejected or eroded from distant volcanoes and then accumulated at moderate to shallow depths in the surrounding sea. The abundance of juvenile pyroclastic constituents, such as glass shards, is evidence for contemporary explosive volcanism, and justifies terms such as 'tuff' or 'tuffaceous' being applied to these rocks (e.g. Fisher, 1961; Table 1 of the Glossary, in the present volume). Processes of devitrification have largely obliterated the more delicate textural details of the finer-grained glassy material, however. In addition to this primary pyroclastic component, it is probable that many of these beds contain material that has been secondarily reworked, rather than representing the in-situ products of direct pyroclastic fall out. Good evidence for this is provided by sedimentary structures such as the normal grading of thinly-bedded or laminated layers, which indicate final deposition from turbidity currents. Even the thickest and most massive beds occur in sequences that have been disturbed prior to their consolidation, resulting in spectacular examples of soft-sediment disruption.

BRADGATE PARK (SK 535 115)

J. N. Carney and T. C. Pharaoh

Introduction

Bradgate Park is a local conservation area consisting of rolling heathland studded with craggy knolls. Its size (Figure 2.8, p. 34), and the fact that it contains palaeontological localities of international importance (Chapter 8), justify its selection as one of the principal Charnwood Forest GCR sites. In addition, many of its exposures serve as type sections for units within the Maplewell Group and overlying Brand Group. Intrusions belonging to the South Charnwood Diorites (see 'Introduction', this chapter) occur in the south of the site, but their contacts with the adjacent stratiform sequence are unexposed. The site occupies a structural position close to the hinge zone of the main Charnian anticline (Figure 2.1), and is one of the few areas of Charnwood Forest suitable for demonstrating geometrical relationships between folds mapped at outcrop scale and the regional Charnian cleavage.

The importance of this site is reflected by its frequent mention in the geological accounts of Charnwood Forest by Watts (1947), Moseley and Ford (1985, 1989) and Worssam and Old (1988). The principal reference works are the two guides to Bradgate Park by Sutherland *et al.* (1987, amended and reprinted in 1994), but there has since been a review of the stratigraphy and age of the Brand Group (Bland and Goldring, 1995; McIlroy *et al.*, 1998). Consequently, the strata of the Brand Hills Formation, exposed within the Stable Pit at Bradgate Park, are possibly referable to the Lower Cambrian. For this reason the Stable Pit is elevated to individual GCR site status and is described, together with other 'Charnian' strata of probable Cambrian age, later in this volume (Chapter 9).

Description

The oldest unit at the site is the *c.* 330 m-thick Old John Member of the Beacon Hill Formation. Its type section occurs on the crags (Locality 1, Figure 2.8; SK 525 113) surmounting the hill crowned by the Old John Tower (Moseley and Ford, 1985). These exposures are in parallel-laminated to medium-bedded alternations of volcaniclastic mudstone, siltstone and sandstone. The commonest sedimentary structures are graded bedding and soft-sediment deformation, the latter seen as gently wavy bedding, rafted and truncated laminae, and spectacular load structures involving sand-grade material penetrating for up to 0.1 m into underlying mudstone or siltstone beds.

The junction between the Old John Member and overlying Bradgate Formation is defined by the base of the Sliding Stone Slump Breccia, whose middle to upper parts are exposed at the Memorial Crags (Locality 2; SK 5237 1097). This exposure also demonstrates the history of sedimentation of strata underlying the prominent bedding plane that contains the Precambrian fossils described in Chapter 8. The 5.5 m-thick bed forming the base of this sequence constitutes the breccia component; it consists of grey, very coarse-grained to granule-grade volcaniclastic sandstone with, near the exposed base, rafts of highly contorted mudstone or siltstone. The bed loses its sedimentary clasts and fines upwards to a 0.25 m-thick bed of massive sandstone. This is succeeded 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 siltstones and mudstones, with slight normal grading, capped by the fossiliferous bedding plane (Figure 2.9).

The most spectacular development of the Sliding Stone Slump Breccia occurs at the type locality (Locality 3; SK 5309 1134) and is described in some detail by Moseley and Ford (1989, fig. 6). It is composed of abundant contorted sedimentary rafts, some up to 0.6 m long (Figure 2.10), separated by irregular zones consisting of coarse-grained volcaniclastic sandstone devoid of such clasts. The sequence fines upwards, over 9 m, to a prominent bedding plane, but this is too fractured and cleaved to show whether fossils are present.

Intermittent exposures of the *c.* 500 m-thick Hallgate Member, basal to the Bradgate Formation, occur to the south of Locality 3. This unit is predominantly composed of fine-grained, parallel-laminated to medium-bedded, volcaniclastic lithologies, with further beds of sediment-raft breccia ('slump breccia') near the base.

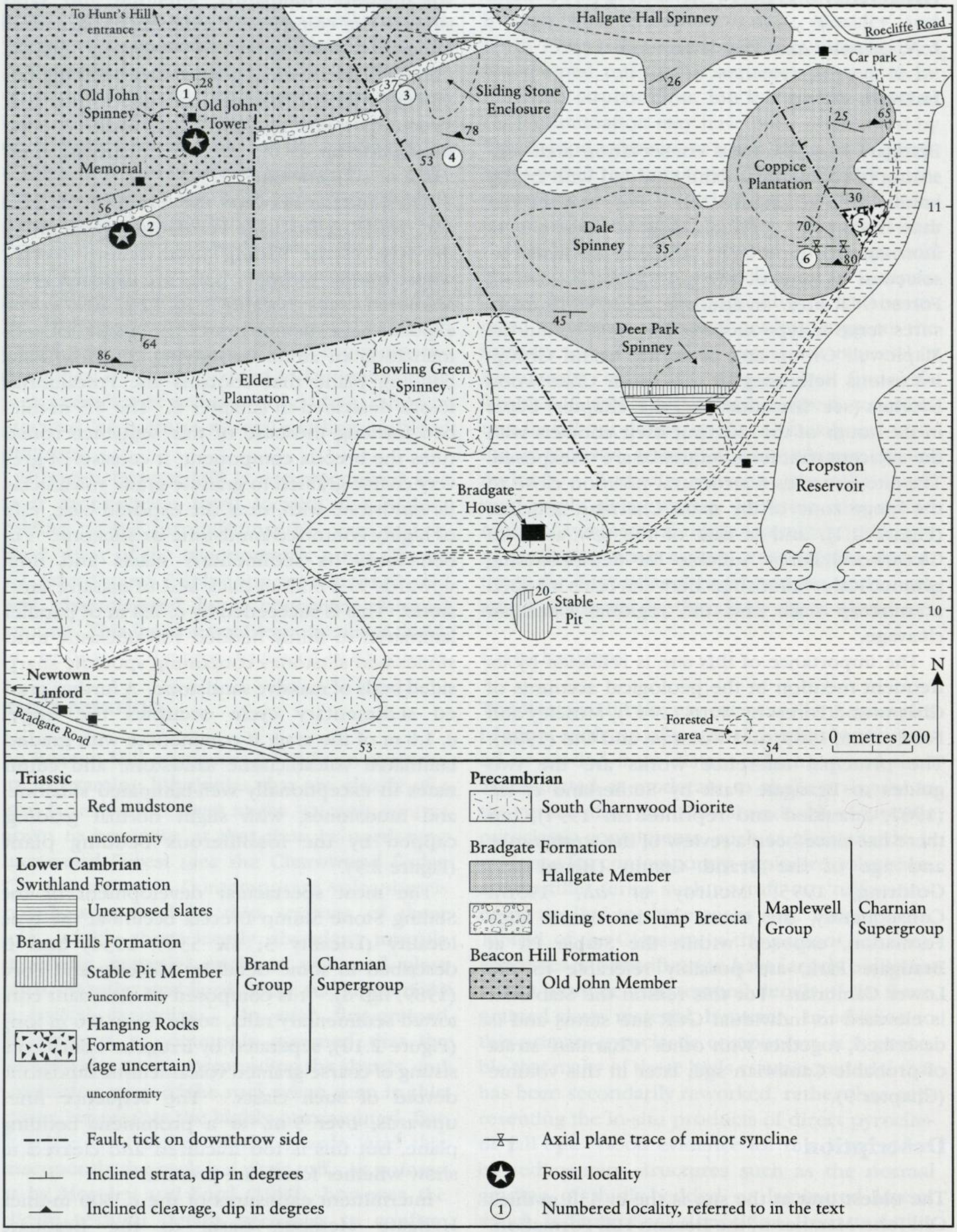

Figure 2.8 Geological map of the Bradgate Park site, adapted from Sutherland *et al.*, (1994) and Kelk and Old (1982).

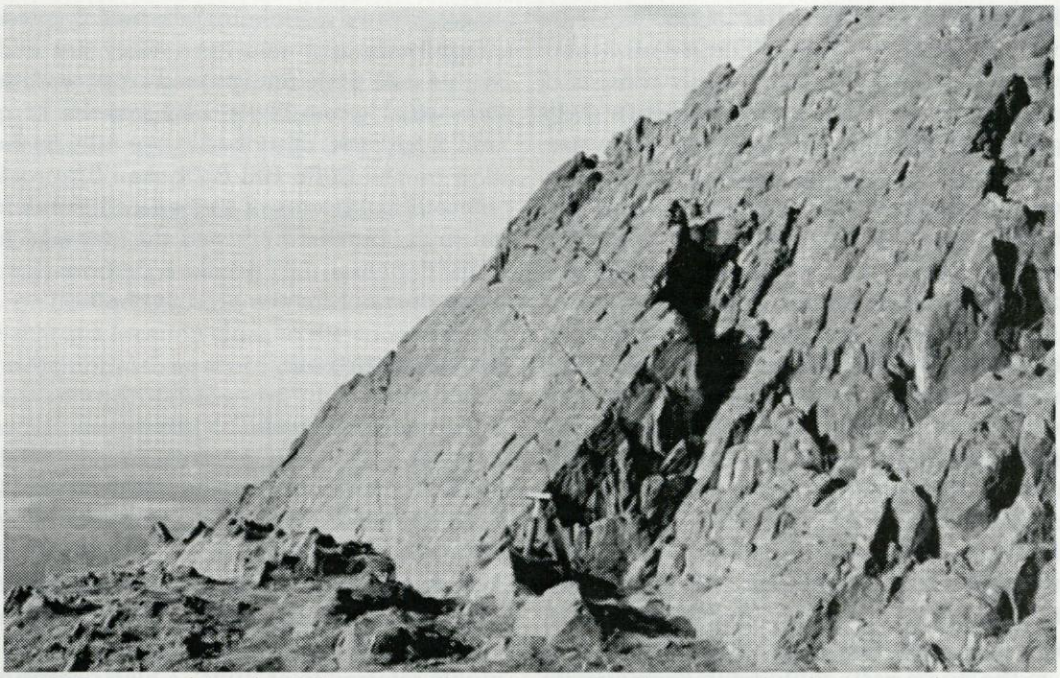

Figure 2.9 Strata overlying the Sliding Stone Slump Breccia Member exposed at the Memorial Crags, Bradgate Park, showing the prominent bedding plane (to left) on which occur fossil impressions (see also, Chapter 8). (Photo: J.N. Carney)

Figure 2.10 Detail of the Sliding Stone Slump Breccia exposed near Sliding Stone Spinney, Bradgate Park, showing tight packing and chaotic orientation of laminated siltstone rafts. (Photo: J.N. Carney.)

Grading within this sequence is displayed at Locality 4 (SK 5315 1113), by repetitive normal grading in successive beds; each graded unit commences in very coarse-grained to granule-grade volcaniclastic sandstone that passes upwards into massive or poorly laminated fine-grained sandstone. In the same 1.5 m-thick sequence, the stratigraphically higher graded beds are thinner and commonly lack a coarse-grained basal layer.

Locality 5 (SK 5424 1100) exposes the Hanging Rocks Formation, defining the base of the Brand Group; better exposures of this unit occur at the Outwoods–Hangingstone Hills GCR site (this chapter). At Bradgate Park, the principal controversy revolves around the low topographical position of the Hanging Rocks Formation, relative to older strata of the Hallgate Member (Bradgate Formation), which occur on the hillside several metres above. The two alternative explanations for these field relationships, discussed in Sutherland *et al.* (1994), were that either this conglomerate lies within the Hallgate Member (and is therefore unique), or that it belongs to the Brand Group but occupies a channel cut into the member. A third explanation suggested here is that this limited exposure forms part of a faulted inlier of the Brand Group. The 3–4 m of exposed strata mainly consists of conglomerate with rounded to subangular clasts ranging from granules to pebbles of 20 mm size; the interstitial matrix is of coarse-grained, poorly sorted sandstone. Clasts of pale to dark grey mudstone occur near the top of the conglomerate. Particularly large pebbles,up to 80 mm across, are common in the lower 1.5 m of the conglomerate; they mainly consist of pink to cream, fine-grained tuff. The conglomerate shows a steeply dipping junction with grey, poorly sorted, medium- to coarse-grained, volcaniclastic sandstone containing thin pebbly lenticles. The roundness of these pebbles indicates that this sandstone is part of the Hanging Rocks Formation, rather than representing substrate of the Hallgate Member. This '2-D' exposure does not allow bedding dip to be estimated; however, a steep dip away from the observer (i.e. to the north-east) could be in keeping with the slope of the sandstone–conglomerate contact. A preferred orientation of spindle-shaped conglomerate pebbles defines a fabric dipping at about 75° to the NNW. This is almost certainly not depositional but is due to stretching associated with development of the local cleavage.

At Locality 6 (SK 5405 1085) a gently folded sequence of volcaniclastic, turbidite-facies mudstones, siltstones and sandstones demonstrates refraction of the main Charnian cleavage (Sutherland *et al.*, 1994). At outcrop the cleavage trace appears to be broadly axial planar with the *c.* 90° trend of a minor synclinal axis. However, when bedding dips and cleavage orientations from this locality are plotted stereographically, it is apparent that the mean cleavage pole is offset in an anticlockwise sense from the fold-girdle representing the best-fit to bedding poles, the angle of offset being 8°. Moseley (1979) had earlier described transection of folds by cleavage throughout most of Charnwood Forest, inferring that the formation of cleavage post-dates the development of the folds.

Isolated exposures of intrusive rocks belonging to the South Charnwood Diorites ('markfieldite') occur near Bradgate House (Locality 7; SK 5337 1013). The smoother surfaces show the medium- to coarse-grained, inequigranular textures and mottled appearance that is typical of this lithology. The pale green rectangular crystals consist of partly albitized and epidotized plagioclase feldspars, and dark grey areas represent aggregates of mafic minerals (mainly secondary amphiboles and chlorite). They are enclosed within pale pink, fine-grained areas representing interstitial granophyric intergrowths of quartz and K-feldspar, described more fully in the section on the Cliffe Hill GCR site. The rocks are affected by systems of well-spaced, sub-horizontal joints but have resisted the cleavage formation defining the Acadian deformation (see 'Introduction' for the present chapter).

Interpretation

Bradgate Park, with its numerous accessible exposures, is an important area in which to study the sedimentology of the Beacon Hill and Bradgate formations (e.g. Sutherland *et al.*, 1994; Moseley and Ford, 1989). The fossils found at certain levels within this succession indicate deposition of these strata in a marine environment. Although these rocks are commonly referred to as 'tuffs', a high degree of secondary reworking is indicated by the numerous examples of graded bedding; this feature suggests rapid deposition of material by turbulent, sediment-laden currents, to produce typical 'Bouma' turbidite sequences (Bouma, 1962). In this setting the superposition of coarse, sand-rich material over the muddy or silty top of an underlying graded bed can result in a reverse density gradient and this may favour the formation of downward-penetrating load structures within the unconsolidated sediment pile. A pulsed sediment supply is further demonstrated, by sequences showing repetitive normal grading and coarse-tail grading (Middleton and Hampton, 1976), the latter seen at Locality 3 where only the coarse-grained fraction shows a vertical variation. Turbidite beds characterized by a thick, coarse-grained basal facies (Bouma division A) reflect proximity to the source region according to Walker (1967), the principal example being the Sliding Stone Slump Breccia Member. Sutherland *et al.* (1994) noted that although the matrix of this unit is composed almost exclusively of volcanic clasts, juvenile pyroclastic material (vitric constituents and some of the crystals) probably amounts to only half of the fragments. They concluded that the breccia did not originate as a pyroclastic flow but was more likely to have been a subaqueous sediment gravity flow, with a debris-flow component represented by the sediment rafts. The Hanging Rocks Formation is the first unit of the

Charnwood Forest sequence to show rounded pebbles and is inferred to be unconformable or disconformable upon the Hallgate Member; its origin is discussed further in the section on the Outwoods–Hangingstone Hills GCR site.

The relationship of the South Charnwood Diorites to the other lithologies of Bradgate Park cannot be conclusively demonstrated from the outcrops at this particular site (but see the section on Cliffe Hill). Sutherland *et al.* (1994) note that at a location close to the contact, south of the Memorial Crag (Locality 2), there is no evidence of hornfelsing of the sedimentary sequence, suggesting a faulted junction.

The Acadian age of the cleavage, and the regional tectonic implications of the anticlockwise cleavage–fold transection geometry seen at Bradgate Park, are discussed in the introductory section to this chapter.

Conclusions

Bradgate Park contains unrivalled exposures demonstrating the high degree of 'reworking' of sedimentary material within the basin that accumulated the Beacon Hill and Bradgate formations. Deposition was entirely subaqueous and mainly involved the turbulent flow of unconsolidated sediment under the influence of gravity, with a relatively minor contribution by direct primary pyroclastic fall-out or pyroclastic flows. Turbidity currents were active throughout deposition of the sequence, but the Sliding Stone Slump Breccia represents a particularly important episode of instability that produced debris flows derived from the mobilization and subsequent collapse of previously deposited strata. Quiescent conditions prevailing at the end of this event were favourable to the preservation of the delicate, frondose fossils described in Chapter 8. The Bradgate Park succession records, at its very top, a dramatic sedimentary change to conglomerates with well-rounded pebbles in the Hanging Rocks Formation. The final phase of Charnian magmatic activity is represented by intrusions of the South Charnwood Diorites. A penetrative cleavage occurred much later, during the Acadian orogeny, in early Palaeozoic times. The cleavage transects local folds, rather than striking parallel to their axes, suggesting that the deformation was transpressive, with strike-slip and compressional components.

CHARNWOOD LODGE AND WARREN HILLS (SK 465 155)

J. N. Carney

Introduction

This site (Figure 2.11) occupies an area of undulating heathland and rocky knolls within the Charnwood Lodge Nature Reserve. It is important in containing the type area for the Charnwood Lodge Volcanic Formation (Carney, 1994), a unit formerly termed the 'Charnwood Lodge Member' and placed within the Beacon Hill Formation by Moseley and Ford (1985). This is a distinctive sequence, about 1000 m thick, characterized by very coarse-grained to block-rich pyroclastic rocks thought to have been formed in close proximity to active Charnian volcanic centres (Bennett *et al.*, 1928; Watts, 1947). The site also includes good exposures of the Benscliffe Breccia Member (see Figure 2.1), which is an important marker horizon at the base of the formation. A unit named the Grimley Andesite (Carney, 1994), is also represented; it is typical of massive andesites in the Bardon and Whitwick volcanic complexes, and thus may represent a satellitic intrusive sheet. The study of these rocks requires large, accessible and well-lit exposures, weathered sufficiently to emphasize the subtle textural relationships at all scales; this site satisfies all of these criteria.

Description

The Benscliffe Breccia Member (Moseley and Ford, 1985) achieves its greatest thickness, of around 100 m, in this north-west part of Charnwood Forest, where it is exposed in crags around the Hanging Stone (SK 4673 1593). It consists of apparently massive lapilli tuffs and andesitic volcanic breccias whose rough weathering surfaces reflect a very coarse-grained to lapilli-grade matrix. Andesite blocks in the breccias are subrounded to highly angular, and across the regional strike they vary in size and in their abundance relative to the matrix. This suggests that the Benscliffe Breccia is stratified, although on a scale that is generally outside the limits of most exposures.

The knoll dominating the central part of the site (SK 4631 1570) is the classic 'Bomb Rocks' locality of Watts (1947). Although this is clearly a fragmental lithology, true volcanic bombs are

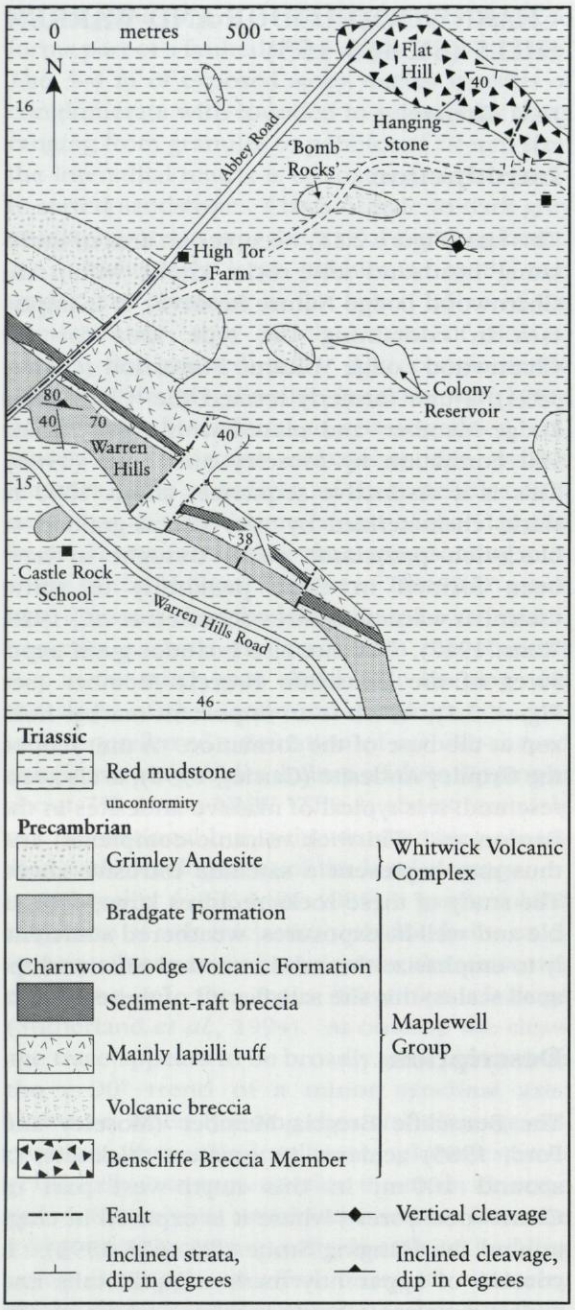

Figure 2.11 Geological map of the Charnwood Lodge and Warren Hills site.

not seen and, instead, most of the fragments are blocks with rectangular, diamond or disc shapes; the rock is therefore better classified as a volcanic breccia (e.g. Fisher, 1961). The blocks constitute up to 60 per cent of the rock and range from a few centimetres up to 1.7 m in size, standing out boldly on weathered surfaces (Figure 2.12). They all appear to be of an identical grey, moderately plagioclase–phyric andesite. Thin sections of similar blocks sampled from volcanic breccias north of Charnwood Lodge show microcrystalline groundmasses devoid of vesicular or amygdaloidal texture, although much detail is obscured by metamorphic recrystallization. Intrinsic to the blocks are deeply weathered, coarse fractures which, rarely, displace the block margins and produce angular corners. Most corners, however, show moderate to low degrees of rounding (Moseley and Ford, 1989), with only a small percentage of blocks having truly angular outlines. Marked changes in clast size and matrix proportions occur around this locality; for example in exposures a few metres to the south-west blocks are smaller and less abundant. Such variations demonstrate that the 'Bomb Rocks' volcanic breccia is part of a thickly stratified sequence. Some flattening and alignment of blocks is seen in the plane of the Charnian cleavage, here sub-vertical and with a sinuous course, deflected around the blocks.

Grimley Andesite forms the crags to the south of High Tor Farm (SK 4594 1542); farther north it is up to 450 m thick within the Whitwick Volcanic Complex (Carney, 2000). Here, it is largely a homogeneous, grey, fine-grained andesite, but on the south-west side of the crags weathered surfaces are rougher and many show narrow, anastomosing zones that divide the andesite into decimetre-size, diamond-shaped lozenges. Freshly hammered samples show that this andesite variant is an autobreccia with a dark green-grey matrix crammed with pale cream, centimetres-size, rounded to angular enclaves that commonly display in-situ breakdown into 1–2 mm slivers. In the small exposure immediately west of Colony Reservoir (SK 4622 1536), lapilli tuff contains irregular screens of massive 'Grimley-type' andesite, suggestive of a contact zone between the two.

The dominating ridge of Warren Hills uniquely exposes the passage from the Charnwood Lodge Formation into overlying strata tentatively equated with the Bradgate Formation. The top part of the Charnwood Lodge Formation, seen on the easternmost knoll of the ridge, is in massive to stratified, coarse-grained tuff and lapilli tuff (e.g. SK 4586 1518). These lithologies are poorly sorted and have crystal-rich matrixes enclosing sporadic (but locally up to 20%) andesite blocks up to several centimetres in size. Farther to the west, and within a few metres of

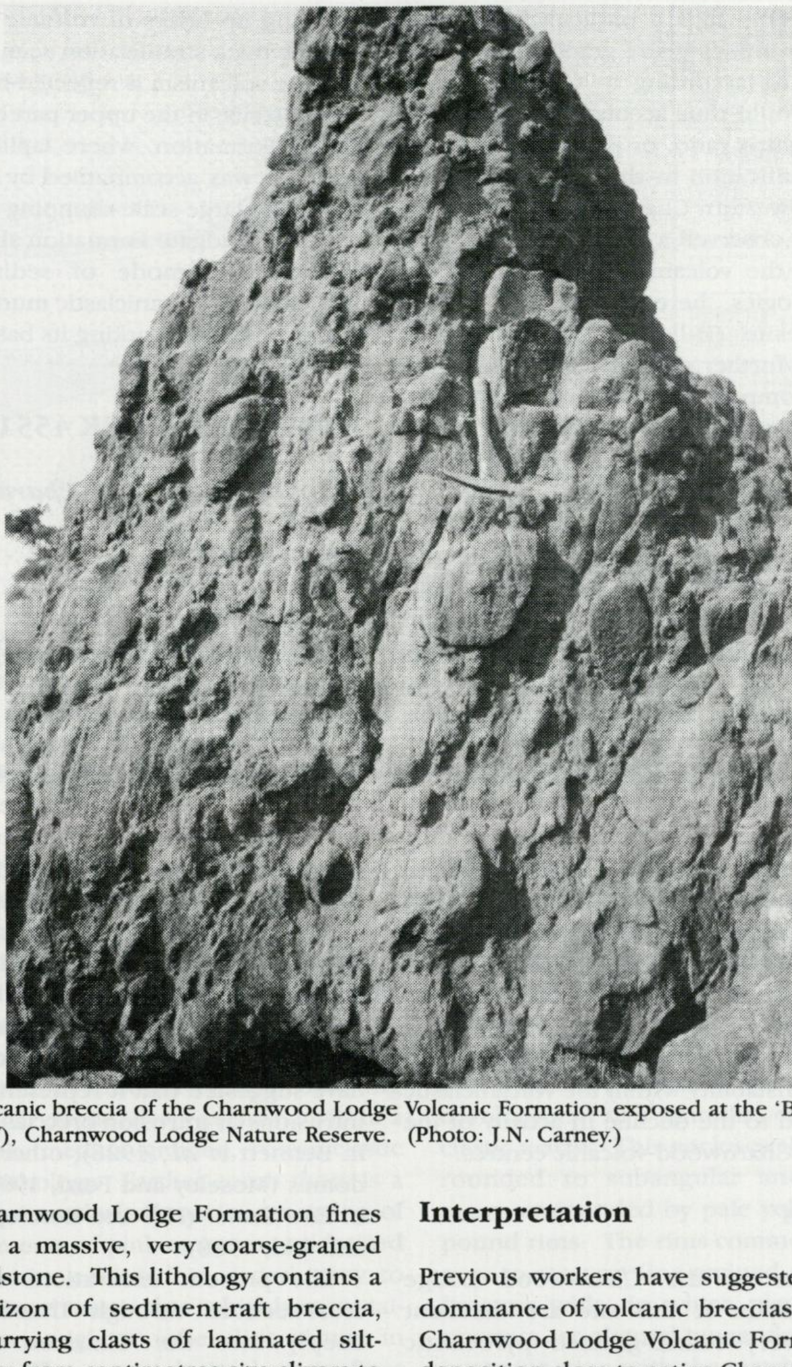

Figure 2.12 Volcanic breccia of the Charnwood Lodge Volcanic Formation exposed at the 'Bomb Rocks' locality of Watts (1947), Charnwood Lodge Nature Reserve. (Photo: J.N. Carney.)

its top, the Charnwood Lodge Formation fines downwards to a massive, very coarse-grained tuffaceous sandstone. This lithology 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 (SK 4574 1516). The base of the overlying Bradgate Formation is unexposed, but is placed just below the first appearance of a thickly bedded sequence dominated by white-weathering, crystal-rich, medium-grained, volcaniclastic sandstones (SK 4573 1515). The bases of individual sandstones are loaded into thin, graded intercalations whose muddy tops locally show folded and disrupted lamination.

Interpretation

Previous workers have suggested that the predominance of volcanic breccias in strata of the Charnwood Lodge Volcanic Formation indicates deposition close to active Charnian volcanic centres. In the Benscliffe Breccia, the thick stratification of the breccias, coupled with their matrix-supported texture and evidence for clast abrasion are consistent with an origin as pyroclastic block and ash flows (e.g. Williams and McBirney, 1979), or as debris flows representing the distal parts of such flows (Carney, 2000). Subaqueous flowage cannot be proved, but would be compatible with the depositional environment proposed for most other Charnian units (Moseley and Ford, 1989). It is a particularly effective mechanism for inducing size grading of clasts in pyroclastic flows according to Cas and Wright (1991), and would thus account for changes in the block-to-matrix ratio, or produce the apparent crude stratification in these Charnian breccias. In north-western Charnwood Forest, there has long been observed a close spatial relationship between the volcanic breccias and more massive lithologies, here represented by the Grimley Andesite (Hill and Bonney, 1891). Recent studies further suggest that blocks in the breccias are comparable in chemistry and petrography to Grimley Andesite. This unit, and its analogue the Bardon Breccia, exposed at the Bardon Hill GCR site, could therefore represent 'feeder' bodies, perhaps lava flows or volcanic domes, their commonly autobrecciated textures reflecting an incipient stage in the process of disintegration that contributed blocks to the surrounding volcanic breccias (Carney, 2000). The Charnwood Lodge Formation is therefore envisaged as a subaqueous volcaniclastic apron surrounding original Charnian volcanic centres.

During the waning phase of volcanic activity, erosion of the edifices was more important than direct pyroclastic contribution, producing deposits of a more epiclastic character. These include the volcaniclastic sandstones at the top of the Charnwood Lodge Formation and base of the overlying Bradgate Formation. This datum is characterized by sediment-raft breccias, seen here and farther east, at the Outwoods and Bradgate Park GCR sites, suggesting that the event causing instability within the volcaniclastic pile was related to the decline in activity of the north-western Charnwood volcanic centres.

Conclusions

The exposures of the Charnwood Lodge Volcanic Formation at this site are excellent examples of very coarse-grained pyroclastic rocks formed in close proximity to the Charnian volcanic centres. The large andesite blocks in the volcanic breccias are comparable in field appearance, as well as under the microscope, to the massive or brecciated rocks represented here by the outcrop of Grimley Andesite. Such similarities suggest that the breccias had formed by the accumulation of blocky material following the collapse of 'Grimley'-type andesitic domes. These dome collapses gave rise to successive pyroclastic block and ash flows and debris flows, building up layers of volcanic breccia, so forming the thick stratification seen in this sequence. Waning volcanism is reflected by a reduced overall grain size in the upper part of the Charnwood Lodge Formation, where lapilli tuffs are dominant. It was accompanied by instability, resulting in the large-scale slumping of beds. The succeeding Bradgate Formation shows a dominantly epiclastic mode of sedimentation, with interbedded volcaniclastic mudstones, siltstones and sandstones marking its base.

BARDON HILL (SK 455133–462132)

J. N. Carney and T. C. Pharaoh

Introduction

The site includes the crags and spectacular viewpoint of Bardon Hill (which at 271 m elevation is the highest point of Charnwood Forest), and the extensive and deep quarry to the west (Figure 2.13). It is unique in being the only locality to expose the Bardon Hill Complex (Moseley and Ford, 1985), a former volcanic centre made up of two components: the Peldar Porphyritic Dacite (new name) and Bardon Breccia (Worssam and Old, 1988). These units consist of a range of massive and brecciated, fine-grained igneous rocks and are in faulted contact with volcaniclastic rocks tentatively equated with the Bradgate Formation. The origins of the Bardon Hill Complex are problematic; some workers have suggested that it represents associations of intrusions or intrusion breccias (Jones, 1926 and in Bennett *et al.*, 1928), others favour volcanic domes (Moseley and Ford, 1985; Le Bas, 1996), or lava flows (Hill and Bonney, 1891; Worssam and Old, 1988).

The present excavations offer impressive cross-sections through Trias-filled valleys cut deeply into the Charnian rocks, uniquely demonstrating the nature of the erosional processes that moulded the pre-Triassic landscape.

Description

The northern face of Bardon Hill Quarry contains the only remaining exposures of the Peldar Porphyritic Dacite ('Peldar Porphyroid' of Jones, 1926). The massive dacite facies of this rock consists of a dark grey to black, fine-grained

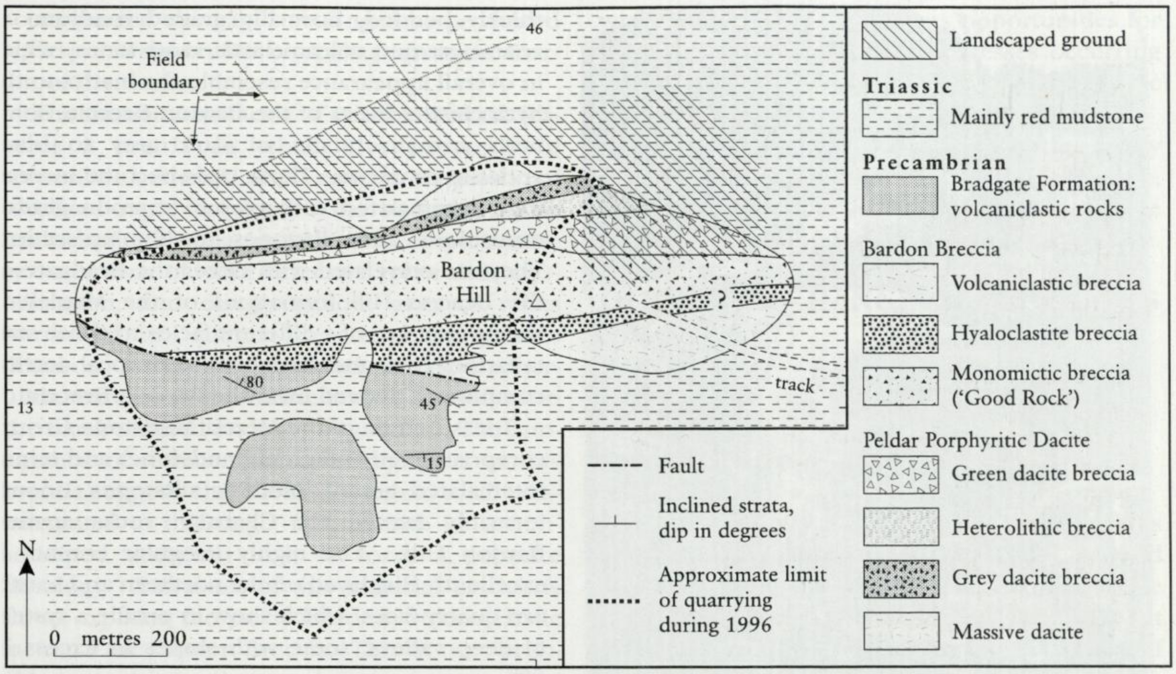

Figure 2.13 Geological map of the Bardon Hill site

matrix enclosing phenocrysts of rounded, pale grey to greenish grey glassy quartz, up to 10 mm across, and more abundant (*c.* 40%) phenocrysts of pink or grey plagioclase; greenish grey microdiorite enclaves are also present.

The contact between the Peldar Dacite and Bardon Breccia is a highly complex zone in which, first, the Peldar Dacite changes to a grey dacite breccia, which may be equivalent to the 'purple porphyroid' of Jones (1926). This lithology passes into a heterolithic breccia consisting of highly angular dacite slivers enclosed within a yellow to pink, medium-grained, volcaniclastic sedimentary lithology. Farther south there is a passage into green dacite breccia, consisting of irregular fragments of pink or green, epidotized porphyritic dacite enclosed in a dark grey to black, fine-grained matrix that is highly recrystallized but shows a 'ghost' spherulitic texture in thin section. The green dacite breccia fines towards the Bardon Breccia, and near the contact becomes penetrated by irregular patches and ribbons of dark red, fine-grained sediment: the contact is sharp but obscured by shearing.

The monomictic facies of the Bardon Breccia shown in Figure 2.13 equates with the 'Good Rock' of Jones (1926). It is a pale green to greenish grey, locally feldsparphyric andesite, intensely epidotized and chloritized. The breccia texture is best displayed on fresh, smooth surfaces that reveal abundant tightly packed, diffuse to sharp-margined fragments of pale green or yellow-green andesite. A rare but highly significant relationship occurs where these fragments exhibit cuspate, 'pseudo-pilloidal' margins part-surrounded by black, fine-grained material. The latter is seen in thin sections to be composed of fibrous chloritic aggregates locally studded with tiny quartzo–feldspathic spherulites. When traced farther south, the breccia texture becomes accentuated due to the development of a granular, crystal-rich, volcaniclastic matrix. This encloses abundant and large, rounded to subangular andesitic fragments, many surrounded by pale yellow or pink, compound rims. The rims commonly feature a dark grey to maroon fine-grained selvage, a few millimetres wide, in which plagioclase microphenocrysts are aligned tangentially along the sharp outer junction with the matrix.

Farther south a hyaloclastite breccia is developed, consisting of a fine- to medium-grained matrix packed with lapilli of spherulitic andesite. It encloses andesite blocks, up to 0.15 m size, which have angular or cuspate margins; they include pale yellow-rimmed andesite, black-rimmed spherulitic andesite (Carney, 1999) and dark grey slivers of the same material. Other fragments include fine- to medium-grained, laminated, volcaniclastic sandstone and sporadic

Figure 2.14 Exposures near Bardon Hill summit, probably in the monomictic breccia facies of the Bardon Breccia. (Photo: J.N. Carney.)

subangular blocks and lapilli of black to purple, fine-grained dacite with small feldspar and quartz phenocrysts. The volcaniclastic facies of the Bardon Breccia, next seen to the south, carries the same types of clast, but the enclosing greenish grey, sandy matrix locally exhibits a diffuse, wispy or contorted bedding fabric.

Natural exposures of the monomictic and possibly the hyaloclastite facies of Bardon Breccia occur on the summit and southern slopes of Bardon Hill, below the trigonometric point and the radio mast (SK 4612 1318). The andesite blocks stand out boldly on weathered crags hereabouts (Fig. 2.14), and some have rimmed margins. On the landscaped site to the north, there are large blocks of quarried rock, which in appearance are typical of monomictic Bardon Breccia seen in the main quarry.

An ESE-trending fault zone separates the Bardon Breccia from volcaniclastic sedimentary rocks. The latter dip southwards and constitute an upward-fining sequence. At the base are thickly bedded, normally graded medium- to coarse-grained volcaniclastic sandstones, which in overall appearance resemble the matrix to the hyaloclastite facies of the Bardon Breccia; some beds contain blocks of dark grey to black andesite or dacite. These beds become increasingly intercalated with grey to maroon graded mudstones and siltstones further up-section. They are correlated with either the Bradgate or the Beacon Hill formations of the Maplewell Group, but are of a different facies to those strata farther east, and contain a major local detrital component derived from the Bardon Breccia.

Triassic strata of the Mercia Mudstone Group, comprising red and green mudstones and minor intercalated green dolomitic siltstones, unconformably mantle the Charnian rocks around Bardon Hill. The highly irregular contact is excellently displayed on the northern and southern quarry faces, which show in profile a system of deep valleys, some with slopes in excess of 60°.

Interpretation

The Bardon Hill site presents opportunities for resolving previous arguments concerning magmatic processes occurring within one of the Charnian volcanic centres. The earliest detailed investigations, by Jones (1926), favoured an 'igneous' origin, as intrusions or intrusion breccias, for the Bardon Breccia and Peldar Porphyritic Dacite. Moseley and Ford (1985), who suggested that the Peldar Dacite formed a small intrusive dome within dominantly clastic rocks, held a similar view. Le Bas (1996) considered that the domes at Bardon were emplaced subaqueously. On the other hand, Worssam and Old (1988) thought that these rocks represented an interbedded sequence of lavas and block lavas, though they did not present conclusive evidence to support this assertion.

The present quarry exposures show many highly significant features, which elsewhere are commonly attributed to interactions between magma and wet sediments (Pichler, 1965; Goto and McPhie, 1998). High-level emplacement of the Peldar Porphyritic Dacite into a cover of unconsolidated Charnian strata is demonstrated, for example, by the sediment-injected, heterolithic breccia developed at its margins (Carney, 1999). The pronounced colour change to the green dacite breccia additionally indicates that hydrothermal activity and epidotization accompanied the rapid cooling that promoted widespread spherulitic crystallization at the margin of the dacite.

The monomictic facies of Bardon Breccia features a matrix in which the presence of spherulitic material, albeit rare, is diagnostic of localized rapid cooling of the andesite. The hyaloclastite breccia represents a complementary outer zone of more extensive spherulitic crystallization, and disaggregation, akin to rocks attributed to 'quench-brecciation' processes (Hanson, 1991); this produced pervasive spherulitic textures in the clastic matrix, as well as in the black-rimmed andesite fragments. The appearance of sedimentary rock fragments in this breccia suggests that the andesite had totally disintegrated at this stage, mixing with its unconsolidated sediment host to form a peperite lithology. Extrusion of this material as debris flows explains the partly bedded, volcaniclastic facies of the Bardon Breccia. This in turn probably passed laterally into the very coarse-grained, volcaniclastic sandstones now seen in fault contact to the south, suggesting that the Bardon Hill Complex was a source of at least some of the detritus that formed the local sequences of the Beacon Hill or Bradgate formations.

Conclusions

Bardon Hill contains the only exposures of the Bardon Hill Complex, and these rocks give a remarkable insight into the magmatic processes that operated within one of the Charnian volcanic centres. The principal conclusion of the earlier research, that these rocks are largely intrusive, is to some extent endorsed by the present deep quarry sections. The emplacement mechanisms of the Peldar Porphyritic Dacite and Bardon Breccia were nevertheless complex since they involved large-scale physical and chemical interactions between the magmas and water-saturated sediments. Some of the Bardon Breccia was eventually extruded, in the form of a volcaniclastic breccia or 'peperite', supporting the suggestion of Le Bas (1996) that the Bardon centre represents activity from an extrusive volcanic dome. However, the term 'cryptodome' (cf. Goto and McPhie, 1998) may be more appropriate since most of the relationships seen here were formed when the Peldar and Bardon Breccia magmas were enclosed in a sedimentary carapace. The significance of the site to Charnian stratigraphy is undoubted, but in a wider context it also presents opportunities for volcanological studies into processes occurring within a late Precambrian high-level magmatic centre.

The quarry sections demonstrate the highly irregular nature of the basal Triassic surface, providing a possibly unrivalled 'snapshot' of the eroded and mountainous pre-Triassic landscape.

OUTWOODS–HANGINGSTONE HILLS (SK 520 157)

J. N. Carney

Introduction

This site occupies a large area of forested hills and heathland and in its southern part, around the Hangingstone Hills, includes the Charnwood Forest Golf Course (Figure 2.15). It is of international importance in terms of Precambrian palaeontology, in that it contains two horizons with fossil impressions, described in Chapter 8. The site additionally exposes extensive sequences in the upper part of the Maplewell Group, and in particular through the overlying Brand Group whose age is currently controversial (see introduction to this chapter). The base of the Brand Group is not exposed but is believed to be an unconformity on which rests pebble beds of the Hanging Rocks Formation (McIlroy *et al.*, 1998), formerly the 'Hanging Rocks Conglomerate Member' of Moseley and Ford (1985). This unit, which represents a significant change in the style of sedimentation, has its type section in the south of the site. It is there overlain by the Swithland Formation, which is now thought to be Lower Cambrian in age, as discussed in the section on 'The Brand' GCR site (Chapter 9).

Description

In the Outwoods area of the site, east-dipping beds are correlated with the lower part of the Bradgate Formation, since they overlie the Outwoods Breccia Member, referred to the upper part of the Beacon Hill Formation. This correlation is further suggested by the occurrence of fossil impressions (SK 5153 1604), which lie in a similar stratigraphical position to the fossil horizon at the Memorial Crags (Bradgate Park) GCR site. This is based on the supposition that the Outwoods Breccia Member

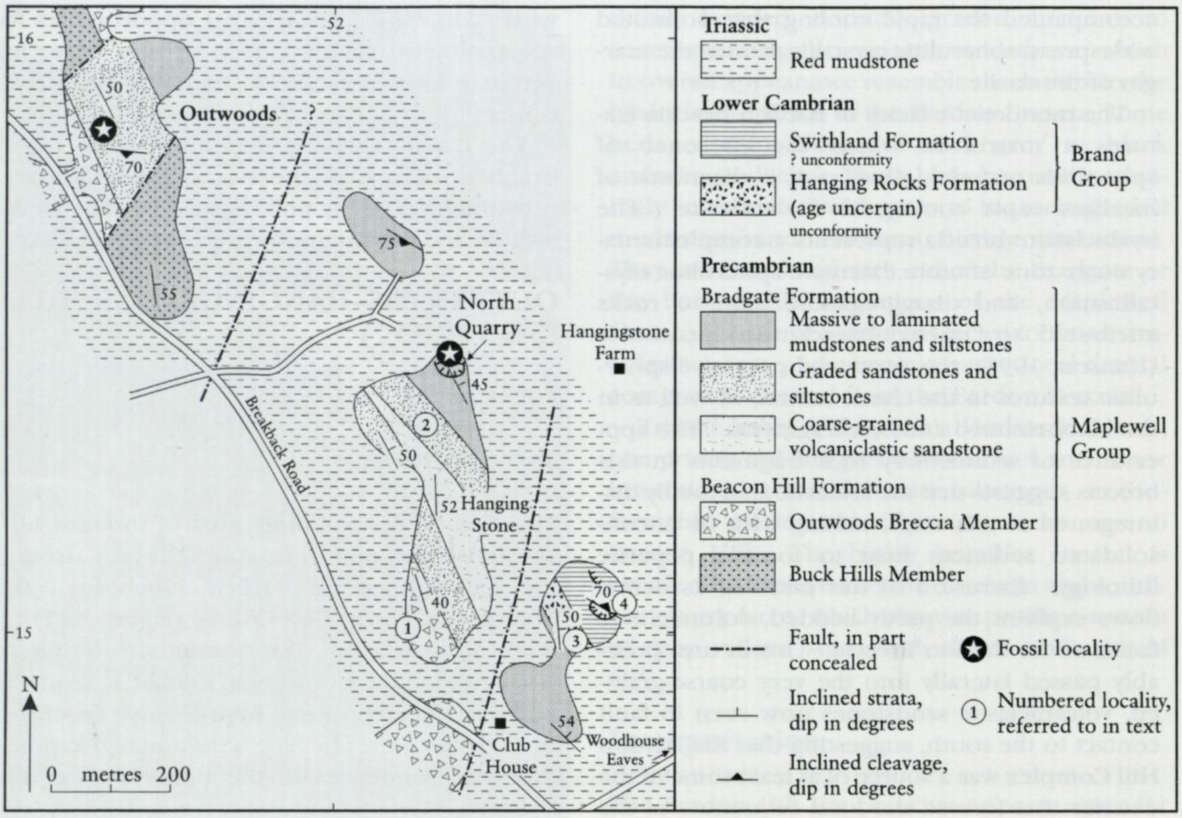

Figure 2.15 Geological map of the Outwoods–Hangingstone Hills GCR site

is a thickened, lateral correlative of the sequence containing the Sliding Stone Slump Breccia exposed in the Memorial Crags. Strata at the Outwoods consist of laminated to thinly bedded, pale grey, volcaniclastic mudstones and siltstones with subordinate beds of massive volcaniclastic sandstone up to 0.4 m thick. Graded bedding and slightly disturbed, gently wavy bedding occur sporadically.

To the south of Hanging Stone, the stratigraphically lowest beds are tentatively correlated with the upper part of the Outwoods Breccia Member. This is regarded as the topmost component of the Beacon Hill Formation (Carney, 1994), although its content of arenaceous beds suggests it could also represent a local base to the Bradgate Formation. At Locality 1 (SK 5218 1501; Figure 2.15) these strata comprise *c.* 6 m of massive, medium- to coarse-grained, very thickly bedded, volcaniclastic sandstone. Many beds are separated by centimetres-thick intercalations of mudstone and siltstone, but these layers are commonly impersistent, due to scouring at the base of the next overlying sandstone; they also show disruption, slump-folding and incorporation as rafts within an invading sandstone matrix. The sequence fines upwards about 100 m to the north, where thinly interbedded siltstones and sandstones represent a transition to the overlying Bradgate Formation.

Beds of the Bradgate Formation exposed at the Hanging Stone crag (SK 5223 1525) are up to 4 m thick (Figure 2.16), internally massive, and composed of very coarse-grained to granule-grade volcaniclastic sandstone. In thin sections there are lapilli of microdiorite and feldsparphyric andesite, but these are subordinate to abundant, irregular-shaped clasts showing relict microcrystalline and spherulitic textures. Individual sandstone beds are separated by thin layers of laminated, normally graded, volcaniclastic siltstone; deeply penetrating load structures are developed at some of these junctions, and slivers or folded rafts of siltstone, up to 0.3 m long, are enclosed within the lower parts of many sandstone beds. The succession fines down, up-section from the Hanging Stone; for example, at Locality 2 (SK 5218 1542), the stratigraphically higher sandstones are medium- to coarse-grained and well-sorted, although still

Figure 2.16 Very thick, massive beds of coarse-grained volcaniclastic sandstone in the Bradgate Formation, exposed at the Hanging Stone. The bedding planes reflect the structural dip, which is to the north-east (from left to right). (Photo: J.N. Carney.)

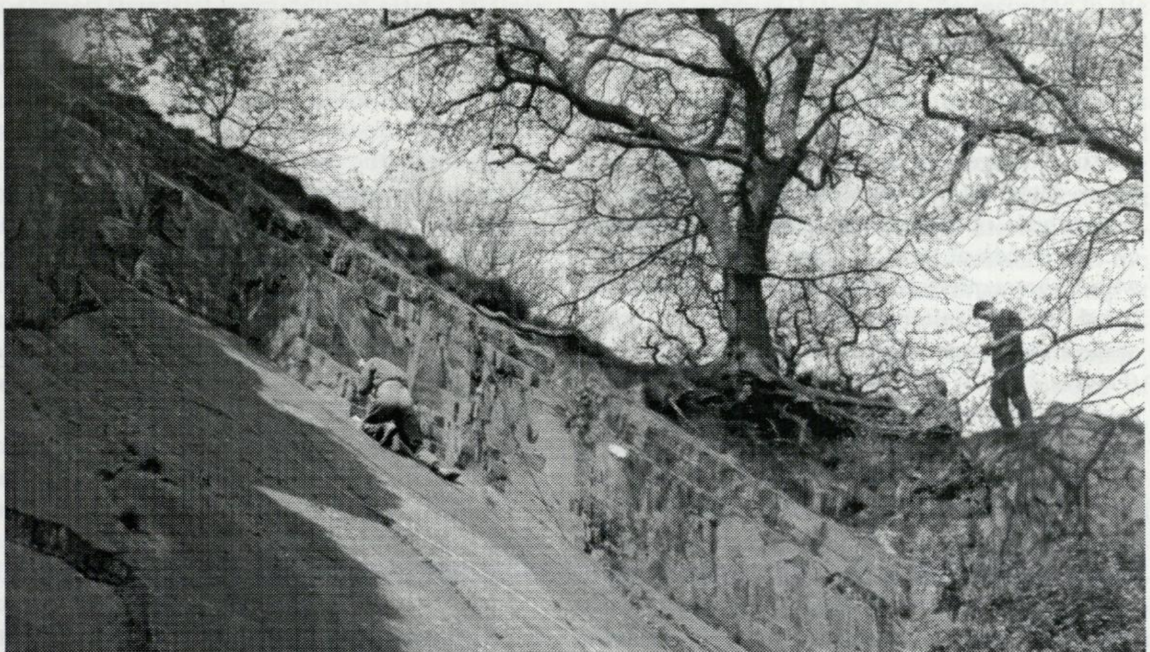

Figure 2.17 Exposures at North Quarry in laminated, volcaniclastic siltstones near the top of the Bradgate Formation. The roped-up figure on the bedding plane is examining Precambrian fossil impressions (see Chapter 8). (Photo: T.D. Ford.)

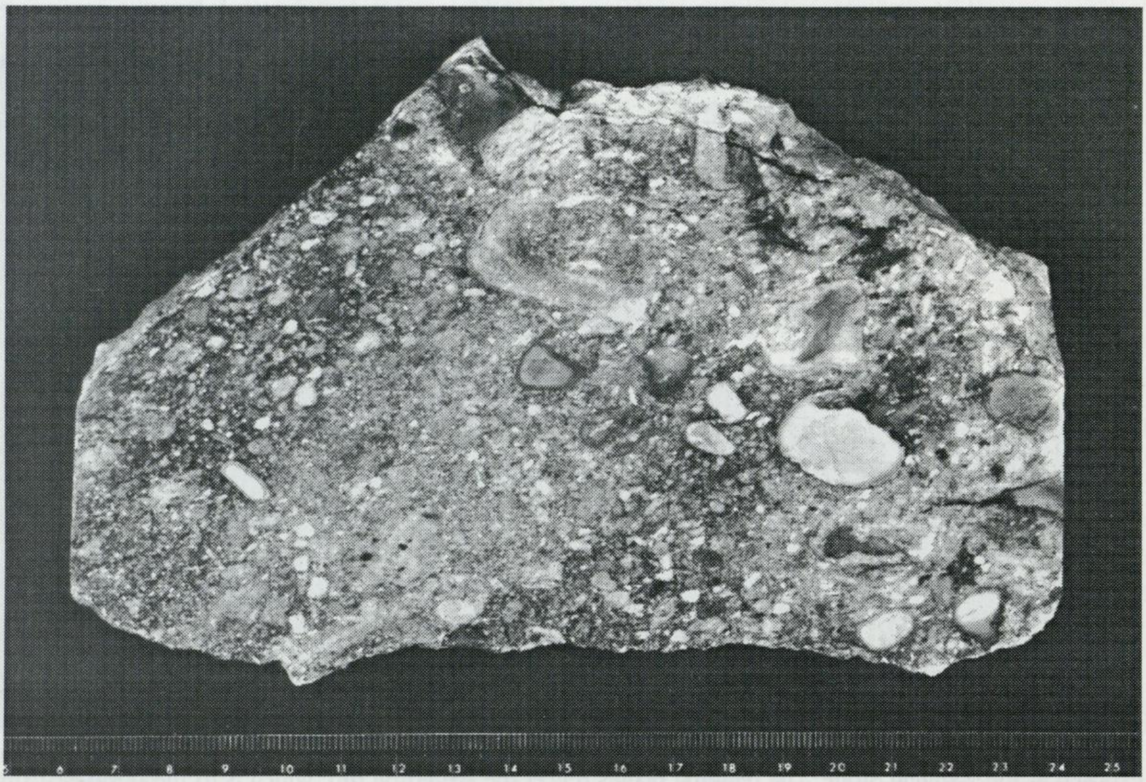

Figure 2.18 Specimen of conglomerate from the Hanging Rocks Formation, Charnwood Forest Golf Course. Note the rounding of the pebbles and extremely low degree of sorting indicated by the range of clast sizes. (Photo: J.N. Carney.)

containing sedimentary rafts. About 40 m to the north, younger beds occur as graded sandstone–siltstone–mudstone packages. The culminating beds of this fining upwards sedimentary cycle are seen at North Quarry (SK 5222 1554), where the sequence mainly consists of parallel-sided beds of alternating volcaniclastic mudstone and siltstone, with subordinate sandstones (Figure 2.17). The mudstone beds are commonly internally structureless, whereas siltstones are well laminated, with sporadic 10–100 mm-thick, sharp-sided beds of fine- to medium-grained, graded volcaniclastic sandstone. The principal bedding plane shown in Figure 2.17 surmounts a sequence consisting of massive to faintly laminated mudstones and siltstones. This is the bedding plane that contains the diverse assemblage of Precambrian fossils described in Chapter 8.

The Hanging Rocks Formation has its type section in the crags to the west of the 18th hole of Charnwood Golf Course (Locality 3). McIlroy *et al.* (1998) suggest two informal divisions, a 'conglomeratic member' at the base, and an overlying pelitic member. The unit's basal contact is now overgrown, but in the sketch by Watts (1947, p. 48), it is shown to sharply overlie 'coarse green hornstones'. The lowest bed presently seen is in massive to plane-stratified, medium-grained sandstone containing a 0.3 m-thick layer of very poorly sorted granule-conglomerate with sporadic, well-rounded larger pebbles (approximately 30 mm size). Resting on this sandstone is a parallel-bedded sandstone about 1.3 m-thick with loaded base. Above this is the main conglomeratic member, about 18 m thick. Its lower part, several metres thick, is composed of matrix-supported granule or small-pebble conglomerate beds *c.* 0.2 m thick, which are separated by similar thicknesses of planar to lenticular sandstone. In thin sections, the conglomerate matrix contains abundant crystals of quartz and plagioclase in a micaceous, mud-rich base. The more common pebbles are of dacite, which shows microcrystalline to fluidal and shardic textures suggestive of derivation from both welded and non-welded pyroclastic rocks. The other clasts are of single or aggregated quartz crystals, some exhibiting internal foliation and sutured grain boundaries; single crystals or aggregates of K-feldspar (microcline and perthite) also occur. A stratigraphically higher bed, about 5 m thick, shows variations in the dominant pebble size, which impart a very crude stratification. Its coarse-grained upper part contains dark grey, intraformational mudstone clasts, 50 mm to 0.1 m across. A polished slab (Figure 2.18), from the middle part of this conglomerate, shows the dominance of the matrix, which is composed of medium- to coarse-grained sand; the clasts range from granules to pebbles up to 35 mm across.

The highest exposed beds of the conglomeratic member are seen north-eastwards across the green from Locality 3. They are predominantly composed of medium- to thinly bedded, massive or normally graded sandstones resting, with loaded bases in places, on laminated tuffaceous siltstone. Conglomerate persists as sporadic layers averaging 40 mm thick, some with pebbles of quartz–phyric tuff up to 20 mm in size. Thin sections of the tuffaceous siltstone matrix to these conglomerates show sporadic crescent- and sliver-shaped shards of recrystallized glass. McIlroy *et al.* (1998) describe a further 30 m of tuffaceous 'red-purple pelites' and greywacke sandstones, which represent a predominantly fine-grained capping to the formation.

Moseley and Ford (1985) note that the base of the Swithland Formation, which may now be referred to the Lower Cambrian (Chapter 9), is exposed on Charnwood Forest Golf Course. They suggest that the top part of the Hanging Rocks Formation is succeeded by '54 m of pelites and very fine-grained greywackes', and, although exposure is not continuous, no sharp junction or obvious unconformity appears to be present within this passage. The Swithland Formation proper is exposed in the old slate quarries at Locality 4. It consists of grey to maroon or purple, slaty mudstones punctuated by thin beds (up to 0.15 m thick) of pale grey sandstone containing mudstone clasts.

Interpretation

This site provides an important record of the sedimentation events leading up to the major hiatus represented by an unconformity inferred between the Maplewell and Brand groups (e.g. McIlroy *et al.*, 1998). At the top of the Beacon Hill Formation, the Outwoods Breccia Member contains coarse-grained strata and sediment-raft breccias. The breccias suggest instability within the sedimentary pile and it is possible that the rapid supply of coarse material, perhaps as pyroclastic flows, increased the local basinal slope angle and created preconditions for plastic deformation within the finer-grained, mechanically weaker layers. The overlying Bradgate Formation shows a phase of coarse-grained sediment deposition, seen as the strata at the Hanging Stone. Those beds are interpreted as the proximal deposits of a turbidite apron, possibly supplied by large-volume pyroclastic flows, that had prograded across this part of the basin. Waning sediment supply, perhaps due to a decline in volcanic activity, is then reflected by upwards fining culminating in the fossiliferous beds of North Quarry. There, the common occurrence of decimetres-thick massive or faintly laminated mudstone suggests deposition dominated by the fall out of suspended clay or silt particles.

Although the base of the succeeding Hanging Rocks Formation is not seen, its content of well-rounded pebbles – the first to be recorded in the Charnian sequence – suggests deposition as a conglomeratic lag overlying an eroded surface on the Bradgate Formation. Rounded pebbles indicate a significant history of transport and reworking such as, occur in fluvial or shoreline environments. Against this is the poor sorting and matrix-supported nature of the conglomerates, their general lack of organization, and the presence of parallel stratification and grading at the top of the unit. These are features reminiscent of the gravelly sand facies (Ghibaudo, 1992), and could indicate a final episode of transport by debris flows or turbidity currents, perhaps in submarine fan or fan-delta environments.

The Hanging Rocks Formation was attributed by Moseley and Ford (1989) to the encroachment of high-energy, shallower water environments following the cessation of magmatism along the Charnian volcanic arc. Individual glass shards have nevertheless been found in siltstones from the unit's upper part, Worssam and Old (1988) noted them in the matrix of some conglomerates, and they have also been reported by McIlroy *et al.* (1998). Volcanism therefore accompanied deposition, but whether this was a continuation of Charnian magmatism, or represents a much later event, depends upon the outcome of a debate over whether the Hanging Rocks Formation is Precambrian or Cambrian in age. Sandstone provenance studies by McIlroy *et al.* (1998) suggest that the formation is more related to true Charnian sequences (Bradgate Formation) than to strata of the Brand Hills Formation that are now believed to be Lower Cambrian (Chapter 9). Against this, the conglomerates contain grains of perthitic K-feldspar and microcline not found in the underlying Charnian strata. Furthermore, the volcanic pebbles differ from typical Charnian acid tuffs both in petrography (Carney, 1994) and geochemistry (unpublished analyses, British Geological Survey). These observations imply that a different volcanic source region now lay adjacent to the Charnian volcanic arc, and that this was sampled by the Hanging Rocks Formation. There is little evidence of the nature of the junction with the Swithland Formation, now believed to be Lower Cambrian, although an unconformity was favoured by McIlroy *et al.* (1998).

Conclusions

This is one of the most important sites in Charnwood Forest, partly because it contains two fossil localities, but also because it provides many exposures vital to interpretations of geological events at the very top of the Charnian sequence. The sedimentary character of the Beacon Hill and Bradgate formations demonstrates that there was an abundant supply of coarse, volcanic-rich, sandy detritus, which was probably introduced to the Charnian basin as sediment-charged turbulent flows triggered by pyroclastic volcanism and/or tectonism. The Bradgate Formation features successive, metres-thick, upwards-fining sedimentary cycles. Two of the finer-grained beds contain important Precambrian fossil horizons (Chapter 8).

These events were succeeded by uplift resulting in the deposition of beds containing the first examples (in Charnwood Forest) of well-rounded pebbles, represented by the Hanging Rocks Conglomerate Formation. Further studies may show whether this pebbly detritus was eroded from the Charnian Supergroup, or from a different volcanic sequence, perhaps that of the Fenland Terrane (Figure 1.1). This major change in sedimentation must be placed in the context of the transition between the unequivocally Precambrian volcanic sequences of the Maplewell Group, and the Lower Cambrian (?) mudrocks of the overlying Swithland Formation. The precise nature and position of this important stratigraphical break is still not known, but further clues may be found in the sequence exposed at this site.

CLIFFE HILL QUARRY (SK 475 106)

J. N. Carney and T. C. Pharaoh

Introduction

The disused Cliffe Hill Quarry near Markfield (Figure 2.19), now commonly referred to as the 'Old Cliffe Hill Quarry', provides extensive exposures that include up to 80 m of stepped vertical sections, enabling a three-dimensional view of the Precambrian rocks (Figure 2.20). It is unique in showing the relationships between Charnian strata containing Precambrian fossils (described in Chapter 8), and the youngest Precambrian intrusive rocks in Charnwood Forest. The quarry serves as the type locality for these intrusions, whose current formal name of 'South Charnwood Diorites' was proposed by Worssam and Old (1988). The same intrusions were classified as syenites by early workers (Hill and Bonney, 1878), but were subsequently named 'markfieldite' by Hatch (1909), after the quarried outcrops by Markfield village 1 km farther east. The informal usage of this name persists today, despite the fact that Wills and Shotton (1934) urged a change to the more correct term 'granophyric diorite'. The most significant aspect of the South Charnwood Diorites is their similarity, both in petrography and geochemistry, to the intrusion of granophyric diorite in Judkins' Quarry at Nuneaton (Chapter 3). This correlation, if confirmed, would imply that the minimum age of the Charnian Supergroup and its included fossils is 603 Ma, as discussed in the introductory section of this chapter.

The site includes impressive sections representing the westernmost exposures of strata equated with the Bradgate Formation (Worssam and Old, 1988), in which the Ediacaran fossils referred to above are found. It also shows excellent profiles through palaeovalleys, or 'wadis', developed along the Triassic unconformity surface.

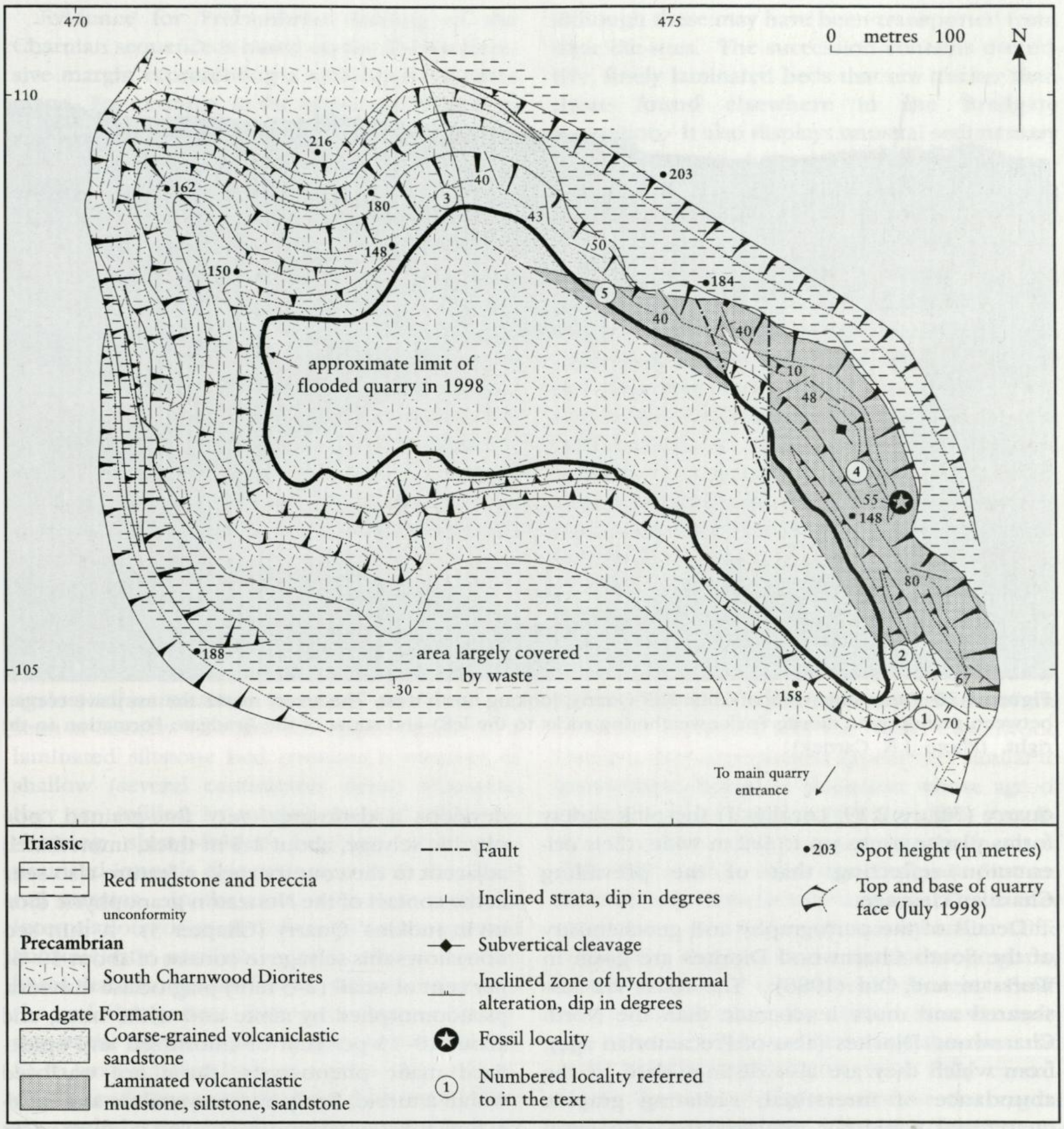

Figure 2.19 Geological map of Cliffe Hill Quarry

Description

The South Charnwood Diorites intrusion is exposed over a width of about 320 m and vertical height of 80 m (Figure 2.19). Except for its immediate contact zone, it is a massive, grey-weathering lithology whose appearance changes little across the entire outcrop. Freshly cut surfaces show a grey, coarsely mottled texture consisting of three principal components. Dark green-grey mafic minerals, mainly augite together with alteration products, comprise about 30 per cent of the rock and form aggregates or individual stubby laths up to 5 mm long. Pale green-grey plagioclase feldspar forms a further 40 per cent, as aggregates or equant to lath-shaped euhedra up to 5 mm long (average 2–3 mm). A finely granular mesostasis, forming the remainder of the rock, represents the granophyric component whose extent of development is the main distinguishing feature of the South Charnwood Diorites; it ranges from grey-green to pink in colour, depending upon the degree of secondary alteration. At the eastern end of the

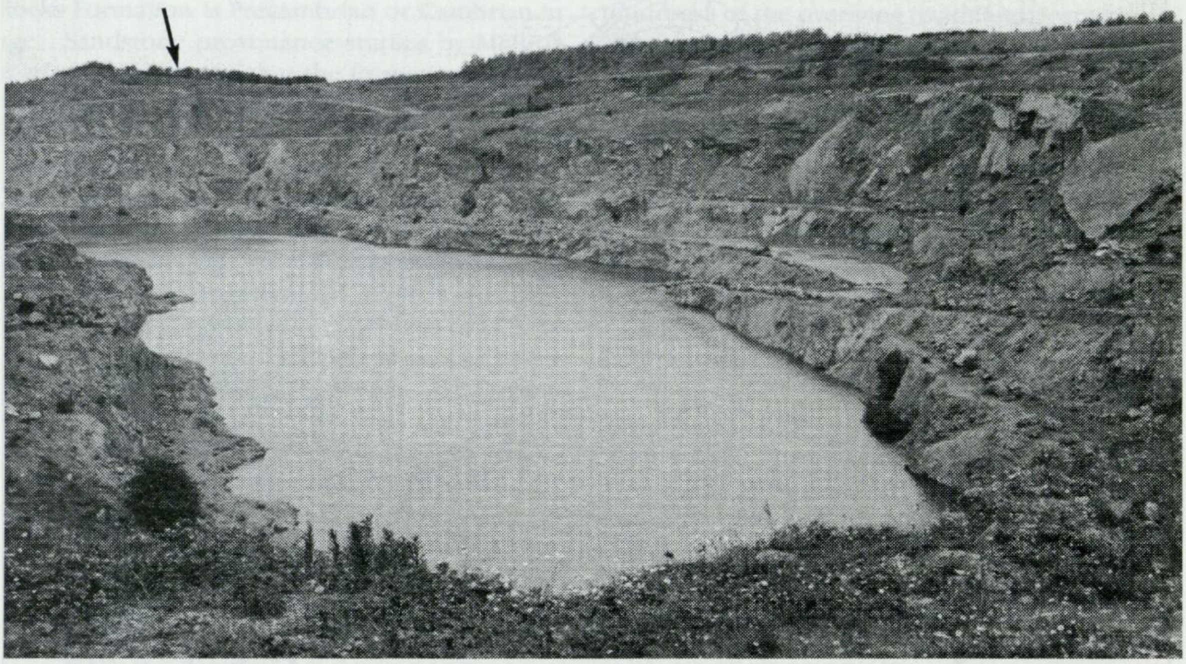

Figure 2.20 Panoramic view of Cliffe Hill Quarry, looking north-west. The arrow marks the intrusive contact between granophyric diorite (paler-weathering rocks to the left) and strata of the Bradgate Formation to the right. (Photo: J.N. Carney.)

quarry (Figure 2.19, Locality 1) the pink variety forms planar zones up to 0.2 m wide, their orientation reflecting that of the prevailing Charnian cleavage.

Details of the petrography and geochemistry of the South Charnwood Diorites are given in Worssam and Old (1988). The rocks are less sheared and more leucocratic than the North Charnwood Diorites (also of Precambrian age), from which they are also distinguished by the abundance of interstitial, radiating graphic quartz and K-feldspar intergrowths. Chemical analyses suggest a range of compositions including granodiorite, quartz diorite and monzodiorite, with quartz monzodiorite the most common type.

The contact between the South Charnwood Diorites and the Bradgate Formation at this site was described as faulted by McIlroy *et al*. (1998); however, it is tectonically displaced only in the central part of the exposure (Figure 2.19). Elsewhere, as noted by Worssam and Old (1988), the intrusion darkens and fines progressively in grain size within about 10 m of the contact, indicative of chilling. At localities 2 and 3, the present authors found that the intrusion develops a dark grey, very fine-grained, porphyritic selvage, about 1.5 m thick, immediately adjacent to the country rock, a feature also seen at the contact of the Nuneaton granophyric diorite in Judkins' Quarry (Chapter 3). A thin section shows this selvage to consist of about 50–60 per cent of small (2–3 mm) plagioclase euhedra, pseudomorphed by albite and white mica, and about 10–15 per cent of chloritized and epidotized mafic phenocrysts; these are enclosed within a turbid, finely microcrystalline and locally flow-foliated groundmass. The country rocks are bleached to a pale cream, fine-grained lithology over several centimetres adjacent to this chilled zone (Locality 2), and farther north, bedding is sharply truncated at the margin of the porphyritic intrusive facies (Locality 3). Contact-related 'metasomatism' was described from Cliffe Hill by Boulter and Yates (1987). It is seen as thermal spots that are sporadically developed over several metres adjacent to the chilled diorite margin at Locality 2. The millimetre-size grey-green spots are restricted to certain laminae within the country rocks, and in places are slightly deformed into elliptical structures by the regional Charnian cleavage.

Evidence for Precambrian folding of the Charnian sequence is based on the diorite intrusive margin representing a structural reference plane. For example, in the upper quarry face, to the east of Locality 2, the south-facing limb of a steep flexure in the Bradgate Formation is truncated at the contact. Similarly, the range of dip attitudes in the Bradgate Formation along parts of the northern contact suggests folding unrelated to any later structures affecting the intrusion.

Present exposures of the Bradgate Formation fringe the northern and eastern margins of the intrusion (Figure 2.20). The 1974–1975 BGS survey (Old, 1982), however, showed a large 'xenolith' of these strata enclosed within the intrusion near the central part of the quarry, which is now flooded. In the east of its outcrop (around and to the north of Locality 2), the Bradgate Formation typically consists of green to grey, parallel-laminated, volcaniclastic mudstones and siltstones. They show normal grading and some beds display contorted lamination; one fallen block contains a highly contorted bed, about 0.2 m thick, which has sharp margins against adjacent strata. Erosional structures are seen at Locality 4, where the upper surface of a laminated siltstone bed contains a number of shallow (several centimetres deep) channels; they are infilled by mudstones and siltstones showing slump-folded laminae with pronounced inwards dips with respect to the channel margins. In the same sequence, sporadic intercalations of graded, fine- to coarse-grained volcaniclastic sandstone have sharp, erosive bases that incorporate flames, rafts and slivers of the underlying strata. There is a change of lithology in the northern part of the quarry (Locality 5) to amalgamated beds of crystal-rich, volcaniclastic sandstone, each about 4–5 m thick. They are graded from granule sandstone and breccia at the base to medium-grained sandstone at the top of each unit.

Interpretation

Strata of the Bradgate Formation give a unique insight into the nature of sedimentation of the rocks in the south-west of the Maplewell Group outcrop. In the east of the site, most beds are graded, or form parts of thick, graded sequences, suggesting that they represent a diverse, though predominantly distal, turbidite succession. Such an environment was favourable at times to the preservation of fossils, although these may have been transported from their life-sites. The succession contains distinctive, finely laminated beds that are thicker than those found elsewhere in the Bradgate Formation. It also displays unusual sedimentary structures that include sharply bounded convoluted beds, possibly indicative of slumping caused by syn-sedimentary seismic activity, and shallow siltstone-filled channels. The latter are severally developed along a single bedding plane, and could represent scours formed by swarms of discrete vortices generated by bottom currents in the interval before deposition of the next overlying turbidite bed. A major episode of proximal turbidite deposition is reflected by the incoming of very coarse-grained, thick-bedded sandstones in the north-west of the exposure.

As discussed in the introduction to Chapter 2, the South Charnwood Diorites represent the end-stage of Charnian activity. They are the products of high-K, calc-alkaline magma that was emplaced into an arc of increased maturity, subsequent to further subduction-enrichment of the mantle source region (Pharaoh *et al.*, 1987b). Although they are different from the rest of the Charnian sequence, and the North Charnwood Diorites, they nevertheless appear very similar to granophyric diorite at Nuneaton whose age of emplacement is dated at 603 Ma. This correlation, if correct, would suggest that the fossils of Cliffe Hill must be older than that date (but see discussion in introductory section). The former observation of a large sedimentary raft at Cliffe Hill Quarry suggests that magmatic stoping may have been part of the intrusion process. From textures observed at the chilled intrusive margin, it can be suggested that the plagioclase and mafic mineral components were fully crystallized at the time of emplacement, i.e. the magma was initially porphyritic. The granophyre component of the intrusion therefore represents the wholesale, in-situ crystallization of the liquid remaining between these crystals. The apparently uniform development of the granophyric residuum in the South Charnwood Diorites is not entirely reflected under the microscope, which reveals a variety of textures ranging from vermicular to cuneiform (micrographic) types (Smith and Brown, 1988), commonly in a single thin section. Such textures would indicate crystallization during moderate degrees of undercooling of the magma (e.g. Bouloton and Gasquet, 1995).

The exposures at Cliffe Hill suggest that the change in magma type represented by the South Charnwood Diorites was preceded by unspecified deformation, involving flexuring of the Bradgate Formation country rocks. It may be speculated that the cessation of extrusive arc activity closely coincided with this tectonism.

Conclusions

Cliffe Hill Quarry contains important exposures unequivocally showing that the South Charnwood Diorites are intruded into strata of the Bradgate Formation. The latter forms a diverse sedimentary sequence, with thick packages of turbidites of both distal (mudstones, siltstones, rare sandstones) and proximal (very coarse-grained, graded sandstones) facies, the former containing the Precambrian fossils described in Chapter 8. The varying dips of these strata indicate that they had been flexured and possibly folded by the time they were intruded, providing important evidence for a mild deformational event occurring around the time of magmatic cessation of the Charnian arc. Thickening of the crust of the Charnian arc had also occurred by this time, and is indicated by the different geochemistry of the South Charnwood Diorites, relative to the rest of the Charnian sequence and intrusions of North Charnwood Diorites. The date for the intrusive event is 603 Ma, but this value is based on long-range correlations and may be challenged in the light of further work. At the time of intrusion the South Charnwood magmas were partly crystallized and charged with plagioclase phenocrysts, which survive within the narrow porphyritic chill zone of the intrusion. Their distinctive granophyric residuum formed when the magma became undercooled after emplacement. The heat of the intrusion caused the local development of thermal spots within adjacent sedimentary strata.