Precambrian Rocks of England and Wales

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Chapter 9

Sites with rocks of possible Lower Palaeozoic age

INTRODUCTION

J. N. Carney

This chapter features three GCR sites that include rock sequences previously thought to be Precambrian, but may be now referred to the Palaeozoic. The two Charnwood Forest sites have only recently been reclassified as probably Palaeozoic, and many users of this volume may still regard these rocks as part of the local Precambrian sequence. Describing these sites in a separate chapter, outwith the Precambrian GCR Block (Figure 1.5), emphasizes their distinction from the rest of the Charnian Supergroup and highlights a controversy that is still continuing. For the other site that has been included, at Thornton in Ribblesdale, a Palaeozoic age is strongly suggested even though the evidence is so far indirect, being based on a nearby borehole.

It should be noted that the Monian Supergroup of Anglesey is regarded by some to be Cambrian rather than Precambrian in age, as discussed in the introduction to Chapter 7, but the evidence again is indirect, being based on doubtful palaeontological identifications and correlations with rock sequences in south-east Ireland. One of the problems when considering the stratigraphical position of the Monian is that it occurs within an imbricated system of juxtaposed terranes (Figure 1.1), each representing a sliver of Precambrian crust that may be considerably removed from its original position. The Monian is therefore part of the highly complex structural fabric of Anglesey and for that reason it is better described, together with the adjacent rocks of definite Precambrian age, in Chapter 7.

STABLE PIT, BRADGATE PARK (CHARNWOOD FOREST) (SK 5340 1000)

J. N. Carney

Introduction

The Stable Pit is a disused quarry situated within the Bradgate Park Precambrian GCR site (Figure 2.8), the geology of which is described by Sutherland *et al.* (1987, 1994) and reviewed in Chapter 2. It provides virtually the only suitable exposures of quartzose sandstone beds developed in the Stable Pit Member, which in turn belongs to the Brand Hills Formation of the Brand Group, Charnian Supergroup (Moseley and Ford, 1985). A further section in Deer Park Spinney, 680 m to the north-east, is at the time of writing overgrown (Worssam and Old, 1988). This site, along with that at 'The Brand', is of prime importance for demonstrating the sedimentology of strata that are now thought to be of Lower Cambrian age (e.g. McIlroy *et al.*, 1998, and see introduction to 'The Brand' site report). It is the type section for the Stable Pit Member (Moseley and Ford, 1985), although the quartzose sandstones seen here are of an unusual facies, in that they differ considerably from the wacke-type turbiditic sandstones representing the top of the member at 'The Brand' site. The uniqueness of these sandstones in the Charnian context was commented on by Watts (1947, p. 52); they are indeed more reminiscent of lithologies in the Hartshill Sandstone Formation, at the base of the Lower Cambrian sequence in Nuneaton (Brasier *et al.*, 1978).

Description

The principal exposures on the northern side of the Stable Pit (Figure 9.1) are in grey- to pink-weathering, medium-grained, quartz-rich sandstones (quartz arenites), which are extremely compact and 'glassy' on fresh surfaces, and form good crags (Figure 9.2). Bedding traces are best seen on joint surfaces orientated north–south; they are rather faint, and defined by *c.* 20 mm-thick layers of darker grey sandstone, which in one place outline vertically stacked, unidirectional cosets of low-angle planar cross-bedding, the foresets dipping to the north-west.

A structure trending roughly east–west, parallel to the local cleavage, is inferred to occupy the area of non-exposure in the centre of the site because the beds next seen to the south side are vertical to steeply south-dipping (50–60°) in a faulted zone about 8 m wide. The sequence here is heterolithic; it includes a thick bed of slaty mudstone with thin (20–30 mm) layers of quartzose sandstone, passing northwards into alternating mudstone and sandstone beds, and thence to mainly sandstone with rafts or discontinuous lenses of mudstone. The thin quartzose sandstone layers within the mudstones have been described as possible clastic dykes (Moseley, 1979; Worssam and Old, 1988), but Sutherland *et al.* (1987) question whether they may also be sedimentary intercalations, the

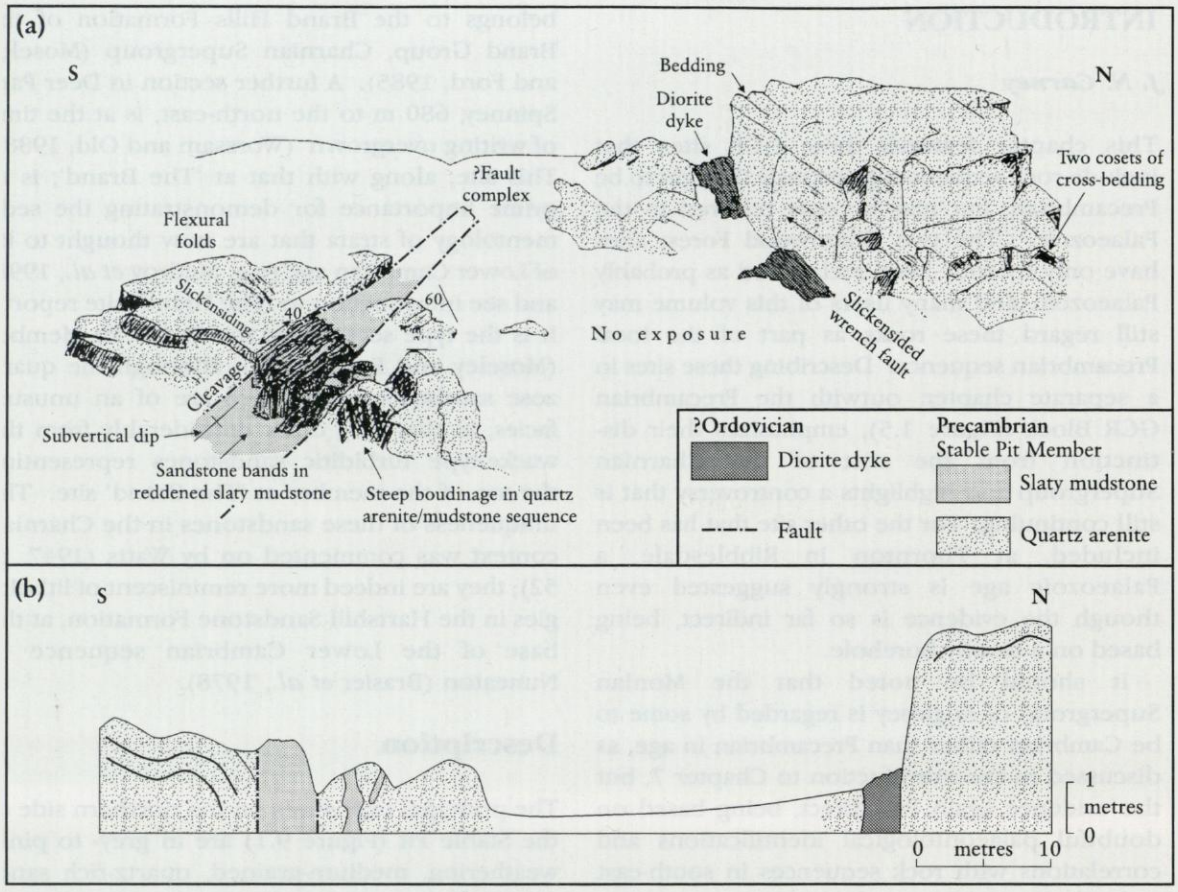

Figure 9.1 Geological sketch of the Stable Pit site (after Sutherland *et al.*, 1994)

explanation favoured here.

A sub-vertical dyke of fine-grained, altered diorite, just over 1 m wide, is intruded into sandstones along the base of the face forming the north-western side of the quarry (Figure 9.2). Its east–west trend appears structurally controlled since it is parallel to the local cleavage strike, and to quartz veins traversing the host rocks. The dyke is also sub-parallel to prominent strike-slip shear zones that give rise to sub-horizontal slickenside lineations in sandstones on the northern side of the quarry.

Interpretation

The Stable Pit sandstones form part of a highly distinctive but rather restricted facies within the Brand Hills Formation. The significance of these lithologies lies in their grey, glassy and obviously quartzose character, and is underlined by the fact that in terms of composition and petrography they compare best with Lower Cambrian strata of the Hartshill Sandstone Formation exposed at Nuneaton (McIlroy *et al.*, 1998). The occurrence of cosets showing tabular cross-bedding is particularly reminiscent of the Park Hill Member at Nuneaton (e.g. Brasier *et al.*, 1978; Carney, 1995), deposited in tidally influenced, nearshore marine environments during the transgression of the sea across the eroded Precambrian landmass. The heterolithic part of the Stable Pit sequence could represent a transition into the mudstone-rich Swithland Formation, in which case the quartzose sandstones could be lateral equivalents of the wacke-type sandstones underlying the Swithland Formation at 'The Brand'. Alternatively, and perhaps more plausibly in view of the comparisons noted with the Park Hill Member, the muddy beds might simply represent periods of reduced arenaceous supply, perhaps during a marine flooding event. The possibility that the quartzose sandstone facies may occupy the lower part of the local Brand Hills Formation sequence is to

Figure 9.2 The Stable Pit, Bradgate Park viewed north-eastwards. The prominent crags at the far side of the exposure are in quartzose sandstones of the the Stable Pit Member, Brand Hills Formation. The rocks in the foreground are part of a heterolithic, sandstone-mudstone facies. (Photo: J.N. Carney.)

some extent supported by an occurrence of the supposedly underlying Hanging Rocks Conglomerate Formation in Bradgate Park, although this occurs 1.2 km to the north-east (Figure 2.8).

The age of the dyke seen at the site is not known. It had been regarded as Precambrian, but if the Stable Pit strata are indeed Cambrian, then it may have been emplaced during the same late Ordovician magmatic event that gave rise to the Mountsorrel granodiorite complex, located to the east of Charnwood Forest (e.g. Le Bas, 1972).

Conclusions

The Stable Pit site offers highly accessible sections in the Stable Pit Member, which has long been considered a unique lithology in Charnwood Forest. Its significance is reinforced by the fact that, on the basis of local correlations, this member is now regarded as part of a Lower Cambrian rather than a Precambrian sequence. Intriguing questions arise over why the Stable Pit Member in its type locality should be so different to the turbidite-facies wackes, assigned to the same unit, at 'The Brand'. For the time being the quartzose sandstones at the Stable Pit are regarded as representative of deposits that were considerably reworked, and 'cleaned' of many unstable constituents, during the early Cambrian marine transgression across the Avalonian landmass (Figure 1.2). In these respects, they are more similar to certain units of the Lower Cambrian Hartshill Sandstone Formation of Nuneaton, than to the rest of the Brand Group. The occurrence of a dyke is another noteworthy feature of this exposure.

'THE BRAND' (CHARNWOOD FOREST) (SK 537 121)

J. N. Carney

Introduction

'The Brand' GCR site is of outstanding importance to British Precambrian stratigraphy in that

it contains excellent exposures of rocks forming the uppermost part of the Charnian Supergroup, the age of which is currently controversial. Watts (1947) had originally proposed a twofold subdivision of these strata, into a 'Brand Series' and an overlying 'Swithland Stage'. This scheme was partly followed by Moseley and Ford (1985), who renamed them the Brand Hills Formation and Swithland Formation respectively, including them within the Brand Group. The real significance of 'The Brand' GCR site centres around the present controversy over the age and stratigraphical affinities of these strata (see also, Rushton *et al.*, 1999). They had always been thought of as Precambrian, but following the discovery of trace fossils in the Swithland Formation (Bland, 1994), and a re-appraisal of the detrital petrography of the lower beds in the Brand Group (McIlroy *et al.*, 1998), they could now be as young as Cambrian. A major unconformity could therefore separate the Brand Hills Formation from the Precambrian proper, although whether this is the unconformity at the top or the base of the underlying Hanging Rocks Formation is debatable (McIlroy *et al.*, 1998; Boynton and Moseley, 1999).

The younger age now proposed for the Brand Hills and Swithland formations implies that these units are part of an extensive Cambrian sedimentary sequence that flanks Charnwood Forest. Such beds are believed to crop out, in contact with late Ordovician granodiorites of the Mountsorrel complex, about 2.5 km to the north-east of 'The Brand' (Le Bas, 1972; see also descriptions of the Buddon Hill site in GCR Volume 17, Stephenson *et al.*, 1999). Further evidence for the nature and age of this Cambro-Ordovician basement comes from several deep boreholes in the East Midlands (Merriman *et al.*, 1993; McIlroy *et al.*, 1998).

The Swithland Formation contains a penetrative cleavage of Acadian (Siluro-Devonian) age (see Chapter 2, Introduction). It has provided the raw materials for a local slate-quarrying industry dating from at least Roman times, but which was curtailed following importation of Welsh slates around the middle of the 19th century (Herbert, 1944). Consequently, at 'The Brand' there are numerous disused quarries and smaller-scale workings for slate (Figure 9.3) and, to a lesser extent, sandstone. Exposure is somewhat discontinuous but there are many excellent sections through the various members and formations of the upper Brand Group.

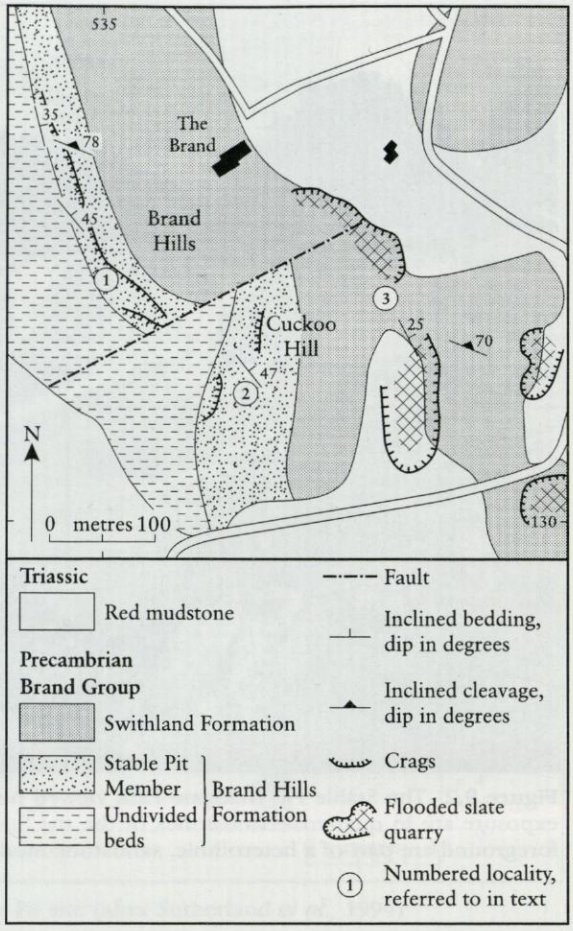

Figure 9.3 Geological map of 'The Brand' site

Description

The revised stratigraphy erected for the Brand Group by McIlroy *et al.* (1998) is followed here. Worssam and Old (1988) referred to the basal unit of the Brand Hills Formation as the Swithland Camp Member. This member, 0–5 m thick and intermittently exposed beyond the western margin of this site (e.g. SK 5332 1330), is distinctive, with abundant, subrounded, disc-shaped, deep purple-grey siltstone clasts in a similarly coloured siltstone matrix. Igneous rock fragments are scattered throughout (Moseley, 1979), one being identified by McIlroy *et al.* (1998) as a granophyric diorite, indistinguishable from lithologies of the South Charnwood Diorites emplaced into the underlying Charnian Supergroup.

The transition from the Swithland Camp Member to the overlying Stable Pit Member is

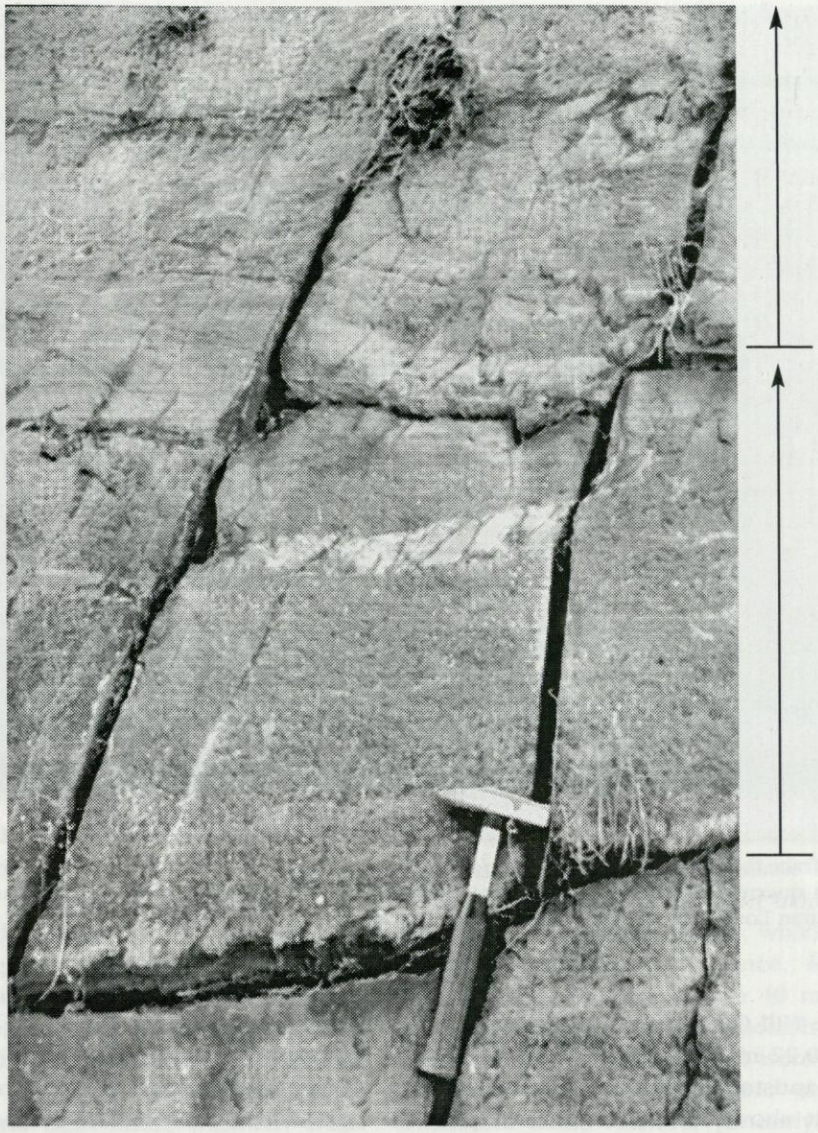

Figure 9.4 Graded sandstone of the Stable Pit Member, Brand Hills Formation, exposed at 'The Brand'. The arrows show two superimposed fining-up sedimentary cycles. Note the sediment raft 'floating' near the top of the lower graded bed. (Photo: J.N. Carney.)

probably gradational at 'The Brand', via a largely unexposed sequence of beds. Boynton and Moseley (1999) have equated these, and the underlying Swithland Camp Member, with a unit that they named the 'Hanging Rocks Member'. The Stable Pit Member is well exposed along the prominent line of crags and quarries on the western flanks of the Brand Hills. Here, a 9 m-thick measured section (SK 5350 1320; Locality 1) shows a sequence of dark grey weathering, medium- to thickly bedded amalgamated sandstones; it is multiple graded, with a superimposed overall fining upwards trend. The lower bed exposed, 0.8 m thick, is typical in showing internal grain size variations producing a diffuse parallel stratification. It also shows normal grading, and coarsens down to dark grey, coarse-grained sandstone with sporadic granules and small dark green-grey pebbles. In thin section these pebbles are shown to be composed of varieties of microcrystalline to spherulitic-textured volcanic or hypabyssal rocks, but there are also dioritic lithologies consisting of plagioclase and alkali feldspar aggregates with patchy developments of granophyre. Some of the latter are texturally similar to the South Charnwood Diorites

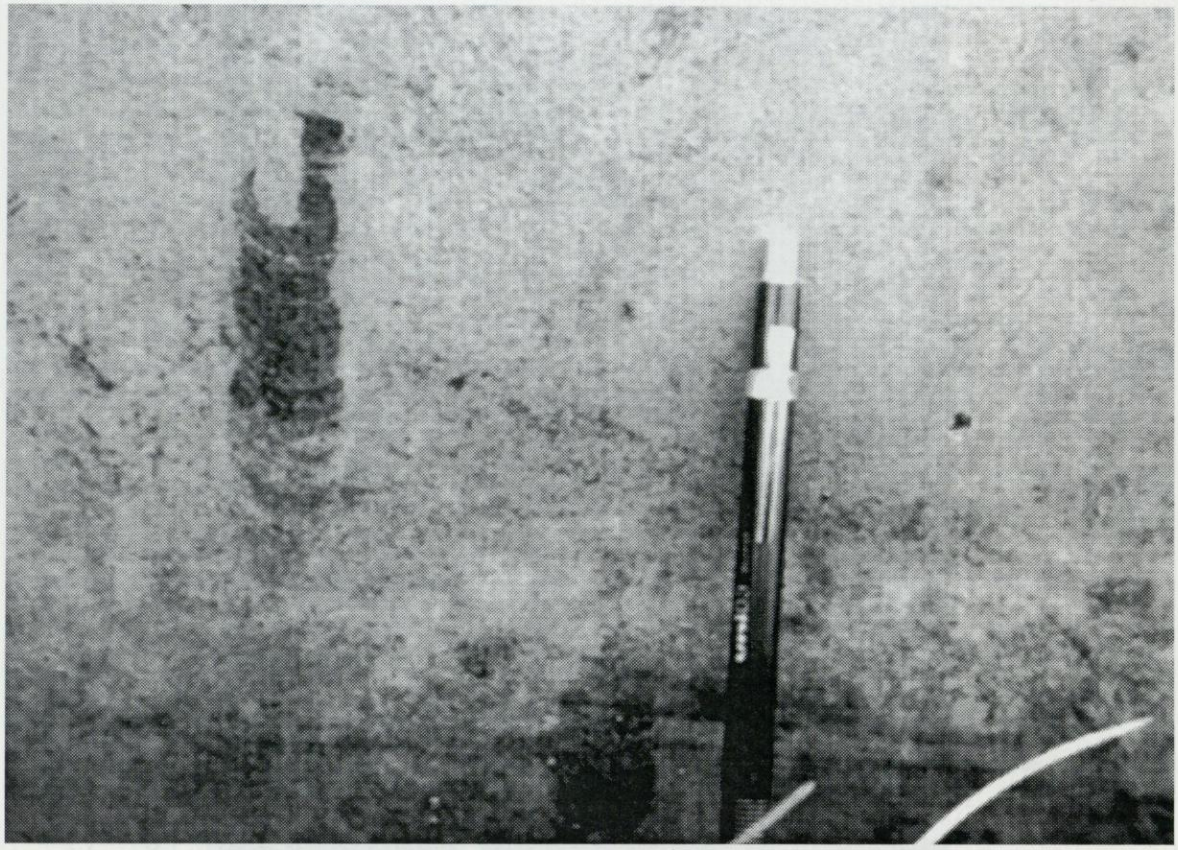

Figure 9.5 Trace fossil, identified as a *Teichichnus* burrow, on a gravestone at Ratby churchyard. The stone was worked from quarries in the Swithland Formation and the trace fossil is of a type that has not been found in rocks older than Lower Cambrian. (Photo: J.N. Carney.)

of the Cliffe Hill GCR site. This is abruptly succeeded by 0.22 m of medium-grained, parallel-laminated sandstone, and then by another graded bed that shows concentrations of pink to green, volcanic and igneous clasts in its basal part. The thin siltstone capping this bed shows erosion and incorporation as rafts into the overlying sandstone, and is in turn succeeded by a further graded bed (Figure 9.4). The stratigraphically higher sandstone beds are up to 2 m thick and predominantly medium-grained; they possess a bedding structure that in places outlines thick sets of faintly defined low-angle cross-bedding.

Around the summit of Cuckoo Hill (Locality 2), exposures show grey, massive to thinly bedded or laminated fine- to medium-grained sandstone with one 10 cm thick layer of matrix-supported small-pebble conglomerate containing angular to subrounded clasts. In thin section these clasts consist of: fine-grained to vesicular volcanic rock, possible tuff, and medium- to coarse-grained granophyric-textured quartz diorite. The stratigraphical position of these beds is uncertain, but the rounding of matrix grains and pebbles, and presence of granophyre clasts, indicates equivalence to the Brand Hills Formation, almost certainly to the Stable Pit Member.

McIlroy *et al.* (1998) note that at 'The Brand', sandstones of the Stable Pit Member are 'greywackes', with well-rounded grains of quartz and metaquartz-arenite, flattened clasts of pelite and sporadic igneous clasts. The sequence also contains sparsely glauconitic greywacke-type siltstones and sandstones, and there is an occurrence of a pipe-like trace fossil comparable to *Arenicolites* sp..

The Swithland Formation, which represents the youngest component of the Brand Group, is exposed in a series of former slate quarries to the south-east of the Brand Hills (SK 5370 1320). Typical lithologies (Locality 3) are medium-grey to purple-grey and from a distance appear to be

massive, apart from sporadic laminated layers that define the bedding. Studies of the highly inaccessible quarry faces by McIlroy *et al.* (1998) have revealed decimetre-thick layers of heavily disturbed strata showing U-shaped *Teichichnus* burrows. This is the first published report of these trace fossils *in situ*, since their discovery on local gravestones carved from 'Swithland Slate' (Bland, 1994; Bland and Goldring, 1995). These in-situ occurrences are flooded and difficult to view, but excellent examples of *Teichichnus* can be seen on certain gravestones in Ratby churchyard (SK 5132 0590), 8 km to the south-west, as illustrated in Figure 9.5. These gravestones also display thin beds of erosively based sandstones showing normal grading and parallel to low-angle cross-lamination (Bland and Goldring, 1995).

The penetrative cleavage typical of the Charnian Supergroup is displayed at 'The Brand', as a WNW (110°), sub-vertical foliation that locally is gently crenulated. Perhaps because of the upper greenschist metamorphic grade of this Acadian event (see Chapter 2, Introduction), the cleavage is rather coarse although still slaty.

Interpretation

The amalgamated sandstones of the Stable Pit Member, forming the lowest exposed beds at this site, are immature and lithics-rich in contrast to the quartzose sandstones of the Stable Pit type locality. The combination of normal grading and parallel- to very low-angle stratification is in keeping with rapid deposition, probably from erosive, sandy to gravelly turbidity currents (e.g. Lowe, 1982). Their content of glauconite is indicative of a marine origin, and it is therefore possible that the member represents material accumulated in a submarine fan environment. Although the sequence is incompletely exposed, it shows evidence of fining upwards, and is thus interpreted to be gradational with overlying mudstones of the Swithland Formation.

The fine sections through the Swithland Formation in the various slate quarries at 'The Brand' have been the focus of much new work since the discovery (Bland, 1994) that the uppermost part of the Brand Group may be Lower Cambrian, rather than Precambrian in age. Important biostratigraphical correlations follow from the fact that the quarry exposures in the Swithland Formation have yielded in-situ occurrences of heavily bioturbated beds containing the trace fossil *Teichichnus* (McIlroy *et al.*, 1998). In the Avalon sequences of Newfoundland *Teichichnus* first appears in the *Rusophycus avalonensis* (trace fossil) ichnozone of the Lower Cambrian Placentian Series (Narbonne *et al.*, 1987), but mudstones churned by *Teichichnus* only occur above the quartz arenites of the Random Formation. The bioturbated horizon is of early Tommotian to early Atdabanian age (Brasier, 1992), and this is therefore the correlation of the Swithland Formation favoured by McIlroy *et al.* (1998). The Swithland Formation contains graded beds and appears to represent a continuation of turbidite deposition, albeit of a more distal facies. Bland and Goldring (1995) discussed the environmental implications of the *Teichichnus* occurrence; although it is not a typical trace fossil in turbiditic mudstones, it has nevertheless been recorded in deep-water sediments of this facies.

As noted by McIlroy *et al.* (1998), the lower sandstones of the Brand Hills Formation, comprising beds of the Stable Pit and Swithland Camp members, generally plot within the recycled orogenic source compositional field of the QFL ternary diagram (Dickinson and Suczek, 1979). They are thus different from the underlying Maplewell Group rocks, which have a dissected magmatic arc provenance. McIlroy *et al.* (1998), describe clasts up to 40 mm across of granophyric diorite from the beds here. In addition, they found that the Nd isotope compositions of similar granophyric clasts in the Swithland Camp Member (underlying the beds exposed at this GCR site) are comparable with those of the South Charnwood Diorites. The clasts therefore demonstrate that intrusions comparable to the South Charnwood Diorites had been unroofed and were undergoing erosion prior to deposition of the Brand Hills Formation. The precise age of these diorites is not yet known for Charnwood Forest, but on the basis of Nd isotope studies (McIlroy, 1996), they are considered equivalent to diorites dated at 603 ± 2 Ma at Nuneaton, which represent the closing stage of Charnian volcanic arc magmatism (Tucker and Pharaoh, 1991). McIlroy *et al.* (1998) went on to suggest that this part of the Brand Group is probably equivalent to the Lower Cambrian Hartshill Sandstone Formation of Nuneaton since certain arenaceous lithologies are petrographically comparable between the

two areas. Nevertheless, it should be stated that the arenaceous strata of the Brand Hills Formation are in aggregate considerably thinner than the *c.* 260 m-thick Hartshill Sandstone, nor do they encompass the same sedimentological and environmental ranges as the latter strata (e.g. Brasier *et al.*, 1978; Carney, 1995).

Conclusions

'The Brand' GCR site is of national geological importance since it contains some of the best exposures in the upper part of the Brand Group, whose age is the subject of a current controversy. The exposures demonstrate a sequence of marine origin, consisting of rapidly deposited turbidite-facies sandstones, in the Stable Pit Member of the Brand Hills Formation, fining up to distal facies, mud-rich turbidites in the Swithland Formation. Clasts in the coarser basal parts of many turbidite beds were apparently derived from the local Precambrian substrate, including the South Charnwood Diorites, indicating an erosional unconformity at the base of this sequence. The location of this hiatus is not yet clear, but it must contain the local Precambrian–Cambrian boundary since the in-situ occurrence of the trace fossil *Teichichnus* in the Swithland Formation indicates that this part of the succession was probably deposited in Lower Cambrian times.

THORNTON AND TWISLETON GLENS (SD 694 700 AND SD 702 693)

E. W. Johnson

Introduction

Thornton and Twisleton glens have been selected as GCR sites because they provide excellent sections through the Ingleton Group of northern England. The group crops out in the Craven inliers, on the south-eastern margin of the Askrigg Block, and is best exposed in Chapel-le-Dale (Figure 9.6). It comprises turbidite sandstones and siltstones that have been isoclinally folded and subjected to low-grade regional metamorphism imparting a distinctive green colour to the strata. These arbitrary characteristics, together with an absence of macrofossils, have previously been considered to indicate that the group is Precambrian, and despite much research its true age remains enigmatic, although indirect evidence reviewed below suggests that it is probably Lower Palaeozoic.

The earliest reference to the Ingleton Group is that by Playfair (1802) who referred to the outcrop in Thornton Glen as 'schistus'. Phillips (1828) included the strata within his 'Slate Series' for which Sedgwick (1852) proposed a 'Lower Palaeozoic' age. Hughes (1867) recognized that there was a stratigraphical break, within the 'Slate Series', that separated greenish grey gritty sandstone and slate (Ingleton Group) from the overlying dark grey slates. The former were therefore in the same stratigraphical position as Sedgwick's 'green slates and porphyries' in the Lake District, for which a 'Caradoc' age had been proposed by Harkness (in Hughes, 1867; p. 354). Hughes recognized that no porphyry was present in the Ingleton succession and dropped the term from the stratigraphical name. The 'green slates' (i.e. the Ingleton Group) are shown as 'Lower Silurian' (i.e. Ordovician) on the primary geological survey and described as 'presumably on the horizon of the Volcanic Series of the Lake District' in the accompanying memoir (Dakyns *et al.*, 1890).

The contradictory evidence for this correlation with the Lake District 'Volcanic Series' caused opinions on the age of the green slates to diverge. Marr (1892) pointed out that the correlation with the volcanic rocks rested on slender foundations, being based on their greenish colour and stratigraphical relationship with the unconformably overlying 'Coniston Limestone'. Marr and W.T. Aveline (in Goodchild, 1892) and Marr (1892) suggested a correlation with some part of a Precambrian succession. Rastall (1907) reiterated this view, emphasizing that the succession consisted of true sedimentary rocks with no resemblance to the lavas, ashes and agglomerates of the Lake District, and to make this distinction clear, proposed the name 'Ingleton Series' for the 'pre Caradocian' rocks. He considered that the apparent conformity of the 'Caradocian' 'Coniston Limestone' on the 'Ingletonian' was probably deceptive, suggesting that the Ingletonian strata were much older than the Ordovician, probably of Precambrian age and equivalent to either the 'Torridonian' or 'Longmynd' groups. From his petrographical study, Rastall (1907) deduced that the 'Ingleton Series' was derived from an igneous and metamorphic complex, Archaean in age, which probably underlay the Pennine area of northern

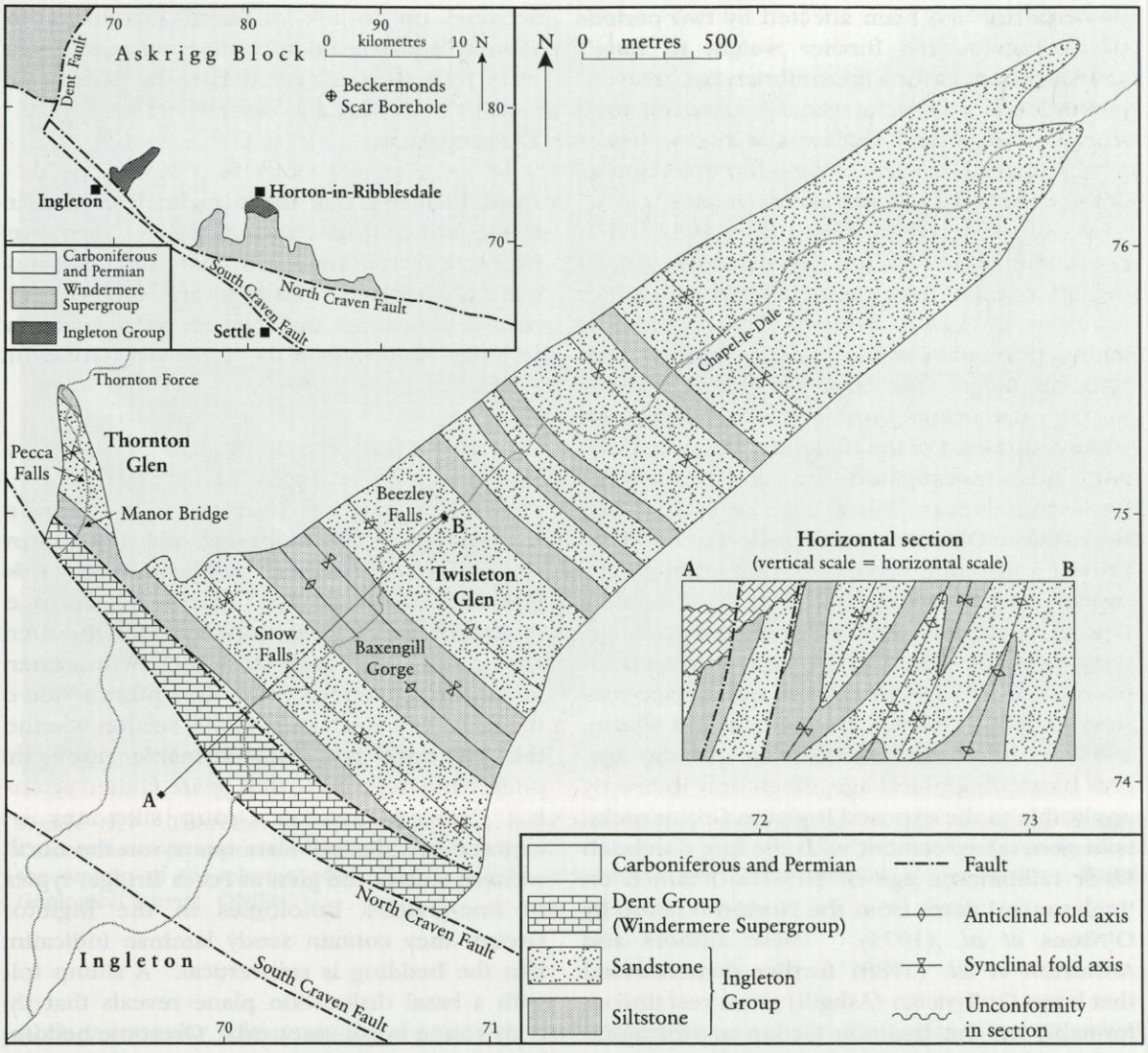

Figure 9.6 Geological map of the Chapel-le-Dale Ingleton Group inlier showing the Thornton and Twisleton glens GCR site

England at no great depth.

The discovery of a limestone neptunean dyke containing an Ashgill fauna at Horton-in-Ribblesdale led King (1932) to emphasize that the 'Ingletonian' was probably Precambrian, since there must have been sufficient time to allow for its consolidation, tilting and erosion before deposition of the Ashgill limestone. Dunham *et al.* (1953) added that King's sequence of events also had to include folding and metamorphism. Furthermore, because there were no known earth movements of sufficient intensity during the Ordovician or Cambrian, the folding must almost certainly be Precambrian. It followed that the 'Ingletonian Series' had to be Precambrian and, on lithological grounds, should be correlated with the 'Longmyndian' of Shropshire.

The sedimentology of the Ingleton Group was investigated by Leedal and Walker (1950), who used cross-bedding and graded bedding structures to demonstrate that the succession was isoclinally folded (Figure 9.6); they also deduced from contemporary slump folds, that deposition occurred on a NW-inclined palaeoslope. The authors recognized the marked contrast between these isoclinal folds and the open fold style of the overlying fossiliferous late Ordovician and Silurian Windermere Supergroup rocks and this led them to suggest that the

'Ingletonian' had been affected by two periods of folding; adding further weight to King's (1932) argument for a Precambrian age. The discovery of a possible organically derived toolmark in fine-grained 'Ingletonian' rocks (Rayner 1957) provided further interest but unfortunately the trace fossil was not age-diagnostic.

Geophysical investigations (Bott, 1961, 1967) revealed that the Ingleton Group forms part of a belt of magnetic basement rocks that underlies northern England. Wills (1978) named this basement domain as the Furness–Ingleborough –Norfolk Ridge. The largest magnetic anomaly on the ridge occurs on the Askrigg Block about 15 km north-east of the Ingleton Group GCR site and was investigated by a borehole at Beckermonds Scar (Wilson and Cornwell, 1982). Beneath the Dinantian cover rocks the borehole proved a turbidite succession that lithologically resembles the Ingleton Group but contains detrital magnetite, which contributes to the magnetic anomaly. One of the samples tested for microfossils yielded an acitarch assemblage considered by R. E. Turner (in Dunham and Wilson, 1985) to be of early Ordovician (Arenig) age. This biostratigraphical age, albeit only indirectly applicable to the exposed Ingleton Group rocks, is in general agreement with the late Cambrian Rb-Sr radiometric age of 505 Ma obtained on 'Ingletonian' slates from the Horton outcrop by O'Nions *et al.* (1973). These authors and Arthurton *et al.* (1988) further demonstrated that latest Ordovician (Ashgill) strata rest unconformably on the Ingleton Group at Horton-in-Ribblesdale, 10 km ESE of the GCR site.

The probable Arenig age of the Ingletonian implies it is contemporary with the Skiddaw Group and the comparable Manx Group (Cooper *et al.*, 1993). However, as these authors point out, the sedimentary characteristics, petrographical compositions and deformation history of the Ingleton Group are sufficiently different to conclude that it is unconnected to the Skiddaw Group and therefore not part of the Leinster–Lakesman Terrane that includes the latter. The two groups might therefore be separated by major, terrane-defining basement faults. The geophysical evidence, discussed above, suggests that the Ingleton Group instead formed part of a belt of magnetic basement rocks on the margins of the Midland Platform – a crustal entity which Lee (1989, pp. 59–63) envisaged as developing separately from the Leinster–Lakesman Terrane. This basement was later accreted on to the northern margin of the Eastern Avalonia microcontinental margin that formed southern Britain during the Ordovician.

Description

In the Chapel-le-Dale inlier isoclinally folded turbidite sandstones and siltstones are well exposed in Thornton (Swilla) and Twisleton glens (Figure 9.6). The rocks are readily seen in natural exposures and quarries adjacent to the popular waterfalls-walk footpath (Johnson, 1994).

Thornton Glen

The lower part of Thornton Glen exposes Carboniferous Limestone on the downthrow side of the North Craven Fault, which crosses the glen near Manor Bridge. Calcareous siltstones of Ashgill age, representing part of the Dent Group at the base of the Windermere Supergroup, are present on the upthrow side of the fault. It is unclear from this section whether the siltstones are unconformable upon the underlying Ingleton Group or are faulted against it. Cleaved Ingleton Group siltstones are exposed in a disused slate quarry on the north-western side of the glen at Pecca Bridge; typical of fine-grained lithologies in the Ingleton Group, they contain sandy laminae indicating that the bedding is sub-vertical. A slump fold with a basal dislocation plane reveals that the beds young north-eastwards. On some bedding planes there is abundant carbonaceous detritus, individual pieces being generally elongate in shape (up to 20 × 5 mm), that is probably organic and of algal origin. The early Devonian Acadian slaty cleavage here is parallel with bedding.

The gradational boundary from the siltstone member into the overlying sandstone unit is visible adjacent to the footpath at the first viewpoint to Pecca Falls. Medium and thick beds of turbidite sandstone are interbedded in the siltstone; they gradually increase in abundance until they become dominant and form the sandstone member that crops out in Pecca Falls itself. Typically the sandstones have planar bed forms and internal sedimentological features characteristic of turbidite sandstones; these include grading (fining upwards of the grain size) and laminated tops discernible in some beds. Together with other sedimentary structures,

Figure 9.7 Thornton Force showing the sub-Carboniferous unconformity in the overhang beneath Carboniferous Limestone; weathered Ingleton Group siltstone crops out below the unconformity and around the margin of the plunge pool. (Photo: A7626, reproduced by kind permission of the Director, British Geological Survey, ©NERC.)

such as irregular sole markings, they show that the sandstone succession continues to young north-eastwards towards a SE-trending synclinal axis immediately above the waterfall. Upstream, the sedimentary structures and siltstone interbeds have orientations that reveal the syncline is asymmetric, with a more steeply dipping south-west limb. The dip angle gradually increases down the sandstone succession, towards Thornton Force.

The sub-Carboniferous unconformity is spectacularly exposed in Thornton Force (Figure 9.7); it represents a time interval of about 150 million years. Sub-horizontal beds of Carboniferous Limestone form the overhang of the waterfall and rest on cleaved Ingleton Group laminated siltstone dipping 70° to the south-west. The unconformity at Thornton Force has played a fundamental part in the development of geology; the relationship was first described by Playfair (1802, pp. 217–19) in his 'Illustrations of the Huttonian Theory', which recognized that unconformites between strata dipping at different angles implied that earth movements must have occurred. The waterfalls-walk footpath continues over the Carboniferous Limestone outcrop and recrosses the unconformity on the way to Twisleton Glen.

Twisleton Glen

Ridges of Ingleton Group sandstone are exposed striking south-east across the fields near Beezleys towards Twisleton Glen, and at Beezley Falls the river Greta cuts a section through sub-vertical turbidite sandstone with siltstone interbeds. Internal sedimentological characters and sedimentary structures, similar to those seen in Thornton Glen, indicate that the succession youngs south-westwards.

At the foot of Beezley Falls, a passage from sandstone up into siltstone is well exposed.

Isoclinal folds with SE-trending synclinal and anticlinal axes are displayed within the siltstone member in Baxengill Gorge. At Snow Falls, where the cleaved siltstone has been quarried for slate, two basic dykes, each about 1 m wide and 7–8 m apart, trend N–S, cutting obliquely through siltstone bedding. The dykes have not been dated but an early Ordovician age seems likely as they are cleaved, and there is no evidence for basic magmatism within the younger Ordovician and Silurian strata cropping out nearby (Leedal and Walker, 1950; Dunham *et al.*, 1953). Possibly therefore, the dykes could be related to the episode of Borrowdale Group magmatism in the Lake District.

Downstream from Snow Falls the siltstone passes upwards into turbidite sandstone and in Twisleton Glen the sandstone is deformed in an isoclinal syncline. Sedimentary structures show that the south-western limb of the isocline is overturned, with the beds dipping 70° to the south-west. The isoclinal fold brings the siltstone member, which is otherwise exposed in Baxengill Gorge and at Snow Falls, back to outcrop lower down the Twisleton Glen. A 2–3 m wide zone displaying slump folds can be seen towards the top of the siltstone near the entrance to the quarry where the cleaved siltstone has been worked for slate. South-west of the quarry, the Ingleton Group outcrop is covered by drift and the contact with Carboniferous rocks at the North Craven Fault is obscured.

Interpretation

The Ingleton Group succession typifies the style of clastic turbidite sedimentation characteristic of deep-water marine environments. The sedimentary characteristics indicate that deposition probably occurred in the middle or lower parts of a turbidite fan. The probable Arenig age of the group, coupled with palaeogeographical reconstructions of southern Britain (Bevins *et al.*, 1992), further suggests that the turbidite fan developed on the northern continental margin of Eastern Avalonia, to the north of the emergent Midland Platform. This would be compatible with the NW-facing palaeoslope deduced from slump folds (Leedal and Walker, 1950) and the igneous and metamorphic clasts derived from an 'Archaean complex' identified in the turbidite sandstones (Rastall, 1907).

Assuming an Arenig age, it would appear that the Ingleton Group was deposited at the same time as the Skiddaw Group in the Lake District, and the Manx Group of the Isle of Man (Cooper *et al.*, 1993). However, as noted earlier, the sedimentary characteristics and petrographical compositions of the Ingleton Group are sufficiently different to conclude that it is unconnected to the Skiddaw Group. Instead, it is probable that the two groups were deposited in separate terranes, these being the Eastern Avalonian margin and the Leinster–Lakesman Terrane respectively. This may also explain the contrast in mid-Ordovician magmatism and deformation styles between the Ingleton area and the Lake District. In the former there are only a few dykes and the strata are affected by two deformations, one causing the isoclinal folds and a younger, Acadian-age event causing the open folds seen in the unconformably overlying Windermere Supergroup of the Horton-in-Ribblesdale inlier (Arthurton *et al.*, 1988). By contrast, the Skiddaw Group was subjected to uplift and extension in the mid-Ordovician, preserving the 8 km-thick Borrowdale Volcanic Group in a regional scale rift zone before Windermere Supergroup sedimentation commenced. There, the only evidence for compression is in the structures of the Acadian orogeny (Cooper *et al.*, 1993).

Conclusions

The exposures in Thornton and Twisleton glens have challenged geologists ever since the beginning of the 19th century, when Playfair (1802) used the unconformity at Thornton Force as evidence for the Huttonian Theory of earth movements, and it is clear that they will continue to do so in the future. One outstanding problem is the enigmatic absence of macrofossils from the succession, since this means that the age of the Ingleton Group – deemed to be early to mid-Ordovician (Arenig) on the basis of acritarchs from a nearby borehole – remains questionable. The sedimentary characters of the turbidite sandstones, and structures in the siltstones, allow the younging directions of the succession to be determined and are instrumental to the identification of isoclinal folds. The presence of such structures emphasizes the contrast in deformation styles between the Ingleton Group and other strata of similar age in northern England, and is critical to the understanding of the tectonic evolution of the Eastern Avalonian continental margin.