The geology of the Lower Cambrian Hartshill Sandstone Formation and Precambrian basement of the Caldecote Volcanic Formation, as exposed in quarries north-west of Nuneaton

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Introduction

This excursion will examine some of the older rock sequences of the Nuneaton Inlier, one of the few areas in central England where Lower Palaeozoic and Precambrian rocks have been brought to outcrop as a result of tectonic uplifts in Variscan and/or Triassic times. The Inlier includes one of the most extensive and complete Cambrian successions in Great Britain, its deeply excavated quarries presenting unique sections across the unconformity with the Precambrian rocks beneath (Figure 1). Much of the geological detail in this Guide incorporates the findings of a recent BGS project to revise the map of the Coventry district (Sheet 169); an accompanying memoir superseding that by Eastwood and others (1923) will be published in due course (Bridge and others, in prep.).

Our present knowledge of the older rock sequences in the Nuneaton Inlier owes much to the pioneering work initiated by Professor Lapworth and his colleagues one hundred and ten years ago. Their discovery of Cambrian fossils in the Stockingford Shale Group (modern names are used) confirmed the doubts already held about the accuracy of the Geological Survey Map (Howell, 1859), which had placed the underlying hard, quartzose sedimentary rocks of the Hartshill Sandstone Formation within the Carboniferous Millstone Grit. It also seemed to confirm their suspicion of a correlation between the Hartshill strata and the lithologically similar Lickey Quartzite of the West Midlands. The Lickey Quartzite was known to be pre-Silurian, but in the light of this supposed correlation Lapworth (1882) revised its age downwards, to Cambrian. It has only very recently been realized that in this sole aspect of geological correlation Lapworth was wrong - the Lickey Quartzite has yielded microfossils indicating a post-Cambrian (probably Ordovician) age (S G Molyneux in Old and others, 1991).

Following more detailed investigations, Lapworth (1886) suggested that the break between the Hartshill Sandstone and underlying, little-deformed rocks of the Caldecote Volcanic Formation may not have been 'of great moment'. However, the Precambrian age of the volcanic succession was confirmed when Lapworth and others (1898) established that the higher beds of the Hartshill Sandstone Formation contained Lower Cambrian fossils, and that the basal Hartshill beds rested with major unconformity on an eroded and weathered surface developed on the volcanic rocks.

The principal objectives of this excursion are to visit the Boon's and Hartshill quarries (Figure 1) in order to examine the Precambrian Caldecote Volcanic Formation, the Precambrian-Cambrian unconformity and overlying Lower Cambrian sedimentary rocks of the Hartshill Sandstone Formation. The following account summarizes the geology, in Part 1, and gives details of the exposures in Part 2.

Part 1 Summary of the geology

Precambrian — Caldecote Volcanic Formation and associated intrusions

The Caldecote Formation is a continuation of the Charnwood Supergroup whose type area is in the Charnwood Forest some 23 km farther to the north-east (Moseley and Ford, 1985). It is the local representative of the 'Charnwood Terrane' (Figure 1) of Precambrian island arc volcanic rocks, which itself is part of a larger crustal massif which resisted the Caledonian deformation and is termed the 'Midlands Microcraton' by Pharaoh and others (1987).

A latest Precambrian age can be suggested for the Caldecote Formation by virtue of its similarity, in lithology and geochemical composition, to the Maplewell Group of the Charnian Supergroup, which has yielded fossils indicative of the Precambrian Vendian Stage (Ford, 1958 and subsequent reviews in Worssam and Old, 1988). Its minimum age is constrained by a U-Pb radiometric date of 603 ±2 Ma obtained on zircon from an intrusion of granophyric diorite (markfieldite) emplaced into the Caldecote Formation in Judkins' Quarry (Tucker and Pharaoh, 1991).

A map of Precambrian rocks within the Nuneaton Inlier is given in Allen (1957). There are few natural exposures, however, and recent BGS work has aimed to unravel the complexity of these rocks through detailed mapping and sampling within the Boon's and Judkins' quarries (Carney, in prep.). This excursion will visit the small exposure in the former, but the following account is largely based on the considerably more extensive exposures in Judkins' Quarry.

The Caldecote Volcanic Formation is a bedded sequence, at least 150 m thick in Judkins' Quarry, of which about 85 per cent comprises crystal-lapilli tuff The tuff occurs as massive, homogeneous beds between 1 and 60 m thick. Crystals are the dominant constituents, and maintain their relative proportions, of about 55% plagioclase and 15–20% quartz, throughout large thicknesses. Many crystals show pristine embayed magmatic outlines, with partial adherences of the original glassy host lava; others have rounded terminations or occur as angular fracture rhombs, commonly displaying complex internal microfracture systems. The matrix of the crystal-lapilli tuff is largely recrystallized but fresher samples preserve the outlines of undeformed vitric shards with silver, bubble-wall or reticulate shapes. In the north-west of the quarry a massive crystal-lapilli tuff bed has a c. 20 m thick capping of stratified and graded crystal-lapilli and crystal-vitric tuff, and tuff-breccia.

Intercalated with the crystal-lapilli tuffs are thin (1–7 m thick) beds composed mainly of tuffaceous mudstone and siltstone with developments of finely-laminated, glass shard-rich vitric tuff. These are particularly well-exposed in Boon's Quarry where sedimentary structures include graded bedding, cross-bedding and water-escape structures indicative of a waterlain origin. Along certain stratigraphical levels in Judkins' Quarry, wet-sediment mixing has occurred between tuffaceous siltstone and crystal-lapilli tuff, forming beds of sediment-raft breccia which are similar to certain of the 'slump breccias' described from the Maplewell Group of Charnwood Forest (Moseley and Ford, 1985).

Two phases of Precambrian intrusion are recorded in Judkins' Quarry. The first, of aphyric and feldspar-phyric basalt and basaltic-andesite, forms a complex of interlinked subhorizontal and subvertical intrusions. The latter have northerly trends and are parallel to, and sometimes spatially associated with, a Precambrian fault system. The second phase of intrusion comprises granophyric diorite (markfieldite) which is also structurally controlled and is elongated parallel to a major north-east trending Precambrian fault. These basaltic-andesite and granophyric diorite bodies correspond, respectively, to the 'North Charnwood Diorites' and 'South Charnwood Diorites' of Worssam and Old (1988).

Interpretation. Subaqueous deposition of the entire Caldecote Volcanic Formation is indicated in the tuffaceous mudstone, siltstone and sandstone beds by sedimentary structures which include normal grading, cross-lamination, convolute bedding and wet-sediment mixing. That the water depths were well below wave-base is shown by the complete absence of wave-generated sedimentary structures. Contemporary volcanism in the hinterland is shown by the content of glass shards in all lithologies and, in particular, by the vitric tuffs intercalated in the finer-grained tuffaceous sequences. The crystal-lapilli tuff beds, with their relatively constant proportions of juvenile crystals, are believed to be pyroclastic rocks (cf. Fisher, 1961) whose overall dacitic composition is indicative of a strong source control. They have been interpreted as welded tuffs by Allen (1957), however thin sections show the matrix shards to be generally undeformed, arguing against post-consolidation welding having occurred on a significant scale. Instead, the crystal-lapilli tuffs more resemble certain types of subaqueous pyroclastic flows which have been described from successions that accumulated marginal to active island arcs (e.g. Fiske and Matsuda, 1964). For example, cracked and brecciated crystals of the type seen here are typical constituents of subaqueous pyroclastic flows (Fisher, 1984), as are the stratified and graded cappings to some of the massive beds in Judkins' Quarry (Fiske and Matsuda, 1964).

Lower Cambrian — Hartshill Sandstone Formation

The entire 260 m thickness of the Hartshill Sandstone Formation, exposed between Boon's Quarry and the neighbouring Hartshill Quarry, is divided into the six members shown in (Figure 2). The formation is perhaps best-known for the thin (2 m) but richly-fossiliferous *Hyolithes* Limestone of the Home Farm Member, which contains the oldest shelly fossils found at outcrop in Britain. The faunas enabled Lapworth and others (1898) to correlate these strata with the Comley and Hollybush sandstones and Wrekin Quartzite of Shropshire (Figure 1). It is now known that the Home Farm Member is also a condensed sequence contemporary with much thicker units in Newfoundland and with an age spanning the lowermost Atdabanian-uppermost Tommotian boundary of the Lower Cambrian (e.g. Brasier, 1989). The Wrekin Quartzite rests unconformably on the Ercall Granophyre which is radiometrically dated at 560 ±1 Ma old (U-Pb zircon method; Tucker and Pharaoh, 1991). This is therefore the maximum possible age for the Hartshill Formation.

The principal published accounts of the Hartshill Formation are by Brasier and others (1978) and Brasier and Hewitt (1979). Recent detailed work in the quarries by BGS has shown this succession to contain a more complete record of sedimentation than had previously been thought (Carney, 1992) and these findings are summarized in (Figure 2), showing the main lithofacies and their interpretation. On the field excursion the sedimentary structures and internal architecture of the various lithofacies will be examined in the light of palaeoenvironmental interpretations summarized below. Summary of sedimentation in the Hartshill Formation.

Palaeogeographic reconstructions and faunal correlations together suggest that strata of the Hartshill Sandstone Formation are the remnants of a late Precambrian to Early Cambrian marine transgressive sequence which covered the western margin of the former Gondwana supercontinent (Brasier, 1980; McKerrow and others, 1992). This continent was fragmented by a phase of rifting that preceeded the development of the Iapetus Ocean (Wilson, 1966).

The coarse-grained red beds in the lower part of the Boon's Member (new name; Carney, 1992) are interpreted as the detritus shed from fault scarps formed during this initial rifting stage. The angularity of the smaller clasts and abundance of lithic and unstable oxide grains are in keeping with sediments transported over a short distance with minimal reworking, rather than with the deposits of a foreshore environment as was originally suggested (Brasier and Hewitt, 1979). In Unit A, the bouldery breccio-conglomerates are the highly immature, chaotic deposits of debris flows formed by mass movement down a nearby steep, unstable, south-west facing palaeoslope; corestones that became detached during collapse of the tropically-weathered Precambrian regolith are represented by the rounded boulders and cobbles in these deposits. The granulestone beds with plane stratification are akin to the deposits of high-concentration sediment gravity flows (Walker, 1978; Lowe, 1982). The overlying Unit B beds contain acritarchs indicative of marine environments of deposition. Their occurrence in massive to plane-stratified sandstone and breccia depositional couplets is reminiscent of proximal turbidite sequences (Hiscott and Middleton, 1979; Ghibaudo, 1992) and suggests accumulation within a fan delta environment. The higher degree of compositional maturity in Unit C sandstones suggests a more subdued hinterland in which sediment was reworked in alluvial systems or along the shoreline prior to eventual deposition. Fan delta influences persisted, forming the more massive beds, but those with tops reworked by wave and/or current processes, suggest that by this time the basin was shoaling to near wave-base depths.

Subsequently, the expanding Iapetus Ocean inundated the rifted continental margin and proceeded inland across eroded Precambrian island arc terranes of the type seen beneath the Hartshill Formation. The transgressive sequence in England was laid down in an epeiric sea within a depositional province known locally as the 'Midland Platform' (Haim and Horton, 1969), and regionally as the 'Avalon platform' (Brasier, 1980).

The first deposits of this major marine transgression formed the beds of the Park Hill Member. At the base, Unit D comprises massive to graded beds, reflecting an intermittent fan delta influence, interspersed with periods of tidal reworking to produce cross-bedded sandstones. Lower shoreface environments were subsequently established in Unit E, in which the complex, herringbone cross-bedded cosets are interpreted to be sections through sandwaves (Dalrymple, 1984) built up by alternating north-eastward and south-westward tidal currents. Subordinate trough cross-bedded cosets are sections through sinuous megaripples formed by east-south-east-directed longshore currents. A relative sea level rise caused the shoreface to retreat landwards, heralding a change to proximal inner shelf environments in which were deposited the mudstone and sandstone beds at the base of Unit F; normal grading suggests that some of these sandstones are the deposits of sediment gravity flows introduced during storms. The younger and thicker beds up-section are the deposits of a prograding sediment wedge that had been worked into dune-like sand waves analogous to the Class I or II bedforms of Allen (1980).

The sedimentologically diverse Tuttle Hill Member was deposited on the inner part of a shelf made wider by continued transgression. It includes intervals, comprising Units G, J and L, which contain graded and/or plane-bedded sandstones interpreted as storm beds deposited during episodes of shelf flooding. At the member's base, the transition from Unit G to H is analogous to the upwards-coarsening trend produced during the growth of an offshore shelf ridge in waters that had deepened significantly following transgression (Hein and others, 1991). The thick packages of tabular-planar cross-bedded sandstones in Unit I represent a post-transgression sea-level highstand period during which sedimentary wedges prograded into the deepening basin. These sediments were worked into dune-like sandwaves (Allen, 1980) which migrated under the influence of a unidirectional, north-eastwards flowing current that penetrated the wider shelf. When this current slackened, perhaps at times of shoaling on the shelf, the compound lenticular cross-bedded sandstones of Units I and K were formed in more unsteady, fluctuating currents, perhaps as stacked sandwaves with scoured and megarippled topsurfaces of the type described by Dalrymple (1984). The storm-induced beds of Unit L represent an unusually thick and homogeneous sequence suggesting a period of extended equilibrium between subsidence and the rate of sediment supply, with long intervals of low sedimentation during which the muddy tops of sand sheets were deeply bioturbated.

The Jee's Member represents a return to wave- or current-agitated environments, signifying lower sea levels relative to those prevailing in the upper part of the Tuttle Hill Member.

A major rise in relative sea level then flooded the shelf, causing the shoreline to retreat and cutting off the arenaceous supply to the basin. The transgression forced the development of the condensed carbonate sequence of the Home Farm Member. The basal Quartzose Conglomerate and Sandstone beds resemble the deposits of a ravinement surface, suggesting the removal by erosion of the upper part of the Jee's Member, either before or during the transgression. Beds of the *Hyolithes* Limestone contain a stable isotopic record that matches the pattern seen in the age-equivalent beds of Newfoundland. The latter show a progressive upwards trend from subtidal to peritidal conditions, suggesting that the shelf was shoaling during the later part of the Home Farm Member (Brasier and others, 1992).

The Woodlands Member is interpreted to be the deposits of a sediment wedge that prograded into the basin during the sea level highstand that followed the transgression recorded in the Home Farm Member. On renewed flooding, the arenaceous source was moved landwards, initiating the minor condensed section respresented by the bioturbated and calcareous beds at the top of the member. Outer shelf environments were subsequently established, in which mudstones of the Stockingford Shale Group were accumulated.

Part 2 Localities to be visited

I. Boon's Quarry [SP 3299 9467]; (Figure 3).

Geology: Caldecote Volcanic Formation; Cambrian–Precambrian unconformity; basal Hartshill Sandstone Formation (Boon's and Park Hill Members); Ordovician lamprophyre sills.

Boon's Quarry (formerly called Man-Abell's Quarry) is a disused and partly filled roadstone working. At the crest of the incline leading north-westwards from the main entrance (Locality 1, (Figure 3)) the views are; to the left, the 58 m-high south-west quarry face exposing a strike section in the Park Hill and Tuttle Hill Members of the Hartshill Sandstone Formation, and straight ahead, the corner on the upper northern quarry level which shows the Precambrian-Cambrian unconformity.

The 'unconformity corner' is one of the primary objectives of this visit. It is a classic unconformity preserved by the Nature Conservancy Council as a Site of Special Scientific Interest (SSSI). Because of this status, we are not allowed to hammer or remove those rocks occurring *in situ!*

Precambrian - Caldecote Volcanic Formation and associated intrusions

Locality 2: Shows a partial succession through well-bedded rocks of the tuffaceous siltstone facies grouping. The grey to green colour of these rocks is in large part due to metamorphic recrystallization to a lower-greenschist assemblage comprising fine-grained chlorite, epidote and white micas. The succession, shown in (Figure 4), consists of a number of coarsening-upwards cycles, one of which (E) culminates in the massive crystal-lapilli tuff of Bed 11.

Tuffaceous mudstone beds forming the base of a cycle appear structureless but polished slabs show they commonly possess an intensely convoluted silty lamination.

The tuffaceous siltstones have well-developed plane-lamination and are cross-laminated near the middle of Bed 4, the current direction being to the south; domical water-escape structures are also displayed in the upper part of this bed. In thin section some silty laminae are composed of vitric tuff, with abundant recrystallized glass shards.

Tuffaceous sandstone forms discrete, 5 to 20 mm-thick parallel-sided and sharp-margined beds which typically occur in tuffaceous siltstone successions near the top of an upwards-coarsening cycle. The medium- to coarse-grained sandstone layers of Bed 3 occur in gradational association with siltstone and mudstone, forming repetitions typical of the 'Bourns' divisions B to E described for distal turbidite sequences. Other sandstone beds show evidence of load-casting and sediment mixing with adjacent mudstone or siltstone. The sandstones are lithic-rich, epiclastic types, mainly containing crystals and fragments of microcrystalline andesite or dacite.

Locality 3: Crystal-lapilli tuff forms much of the quarry face; its coarse-grained texture is well-displayed on the fresh surfaces of fallen blocks at the base of the cut. Plagioclase forms the white to pale pink crystals constituting 50 to 60 % of the rock; they show an extensive overprinting alteration to aggregates of albite, white micas, epidote and carbonate. Many plagioclase crystals are subhedral to rounded and show extensive subgrain development, some having broken down to clusters of angular fragments. Quartz crystals (15–20% of the rock) appear grey and glassy. Virtually all crystals show internal microfracturing, which in the case of quartz is generally disposed radially to the crystal margins.

Blocks account for less than 10 per cent of the crystal-lapilli tuff (they are more numerous in lithic-crystal-lapllli tuff beds in Judkins' Quarry); two types are recognised. Dark porphyritic inclusions, also described by Allen (1957), have ovoid to equidimensional shapes. They have similar crystal contents to the enclosing tuffs but in thin section their dark matrix is highly chloritic and heterogeneous, with banded or fluidal textures in some parts and with other areas showing good preservation of vitric shards. In these respects the inclusions resemble fragments of scoria or welded tuff. Angular lithic blocks, constituting the second type of inclusion, are of fine-grained aphyric to sparsely porphyritic andesite or dacite, welded tuff with compressed vitric shards, and denitrified glass with relic perlitic texture.

A subvertical sheet of basaltic-andesite intrudes crystal-lapilli tuff west of Locality 3. Its upper surface is truncated at the unconformity with the Hartshill Formation.

The Precambrian-Cambrian unconformity

Locality 4: At the 'unconformity corner', coarse-grained breccias and granulestones of the Boon's Member rest on weathered and eroded Precambrian crystal-lapilli tuff. Convex irregularities on the unconformity surface correspond to the tops of weathering spheroids developed in the upper c. 2 m of the Precambrian rocks. Individual spheroids are surrounded by reddened weathering rinds which have tangential 'onion skin' foliation. Within these rinds, the only minerals to survive are granule-size quartz crystals which do not change in shape, distribution or abundance when traced into fresh tuff forming the interior of the spheroids. Thin sections show the weathered rinds to be composed of white micas aggregates wrapped by anastomosing stringers and veinlets filled with opaque minerals.

Two aspects of the Precambrian weathered profile are worthy of discussion. First, the presence of corestones (Brasier and Hewitt, 1979) suggests it can be compared with the type of weathering developed below the saprolitic zone of modern tropical lateritic soil profiles, as described from Uganda by McFarlane (1983). Second, if this analogy is correct then the weathering must have occurred when this part of Gondwana lay at low latitudes. Such a position is to some extent indicated by the palaeogeographic reconstructions for the latest Vendian by McKerrow and others (1992), which place 'Avalonia' at about 35°S. This is nevertheless outside the modern tropics, suggesting either that this type of weathering extended to higher latitudes in late Precambrian-Early Cambrian times, or that the palaeogeographic reconstructions reflect a relatively late stage in a Vendian southwards drift of Avalonia away from the tropics.

Immediately north-east of Locality 4 there is a minor inversion of the succession, with Precambrian rocks overlying a 0.5 m thick mudstone bed along a reverse fault. This mudstone contains a sparse acritarch fauna (genus *Leiosphaeridia;* Molyneux, 1992) indicating that it is a marine bed belonging to the Hartshill Formation. Upwards the fault flattens out to occupy the unconformity surface, which is seen to truncate a Precambrian basaltic-andesite dyke.

Hartshill Sandstone Formation

Localities 4 and 5: Precambrian rocks are unconformably overlain by Unit A of the Boon's Member. The most conspicuous rocks are the breccio-conglomerate beds. These are debris flows containing very large (up to 2m dimension) cobbles and boulders whose rounded shape suggests they are corestones detached from the Precambrian weathering profile; their matrix is composed of poorly-sorted, structureless gravel full of angular fine-grained Precambrian volcanic clasts. The granulestone beds similarly contain abundant lithic clasts, though show better sorting and have a plane-bedded internal structure defined by the parallel orientation of platy clasts and by layers that are relatively impoverished in the larger clasts and/or enriched in the coarse-grained sand component.

Locality 6: The quarry face exposes about 7m of Unit C which is the upper component of the Boon's Member, Unit B having been faulted out. The succession comprises tabular beds of grey litharenite sandstone which lacks the high abundances of opaque and lithic grains seen in the underlying beds. The beds are structureless, or have plane- to low angle cross-bedding. Their topsurfaces are flat to slightly undulatory, suggesting some minor wave or current reworking.

Some of the lamprophyre sills that pervade the Cambrian succession in the Nuneaton Inlier can be viewed here. Related intrusions up to 60m thick near Bedworth have yielded a (late Ordovician) radiometric date of 441Ma (S R Noble, pers. comm, 1992).

Locality 7: The north-western quarry face exposes a succession through the lower to middle part of the Park Hill Member (Unit E). These sandstones are amongst the most quartz-rich of the Hartshill Formation, with sublitharenite or lithic subarkose compositions. The sandstones show herringbone cross-bedding and represent sections through cosets of complex tabular planar cross-bedding (Figure 2). Such a pattern of cross-bedding indicates formation of these beds in a regime of regularly reversing tidal currents, flowing either to the north-east or south-west. Trough cross-bedding is rarely seen, with foreset inclinations usually to the east or east-south-east. Some of the lower bounding surfaces of cosets have scoured bases, and their top surfaces sometimes consist of coarse-grained rippled sandstone. A particularly distinctive feature of the Park Hill Member is the paucity of mudstone drapes between beds.

(Locality 8: Beds of Unit B of the Boon's Member only crop out in the south-east of the quarry and therefore will be viewed out of sequence. The succession here, about 9 m thick, consists of red sandstone and breccia, forming successive depositional couplets interpreted as proximal turbidites. The medium- to coarse-grained lithic arenite sandstones are either plane-bedded or structureless, and the breccia layers are parallel-sided and sharp-based, as shown schematically in (Figure 2).)

2. Hartshill Quarry [SP 336 937]; (Figure 5)

Geology: Hartshill Sandstone Formation; Ordovician lamprophyre sills

The Hartshill Quarry (formerly known as Jee's Quarry) is currently being worked for aggregate. It is approached from the entrance on the opposite side of the road from the main Tarmac office. This excursion will examine the older, north-eastern and south-eastern quarry faces which together expose about 80 per cent of the Hartshill succession.

Locality 1: Bedding plane exposure in Unit E, Park Hill Member. Shows large, scoop-shaped scour pits whose asymmetry of profile indicates a current flow to the south-west (down-dip); associated asymmetric ripple marks were produced during the same current flow. Identical scour pits described from the Early Cambrian of the USA are interpreted as indicating the direction of flow of the ebb current (Simpson and Eriksson, 1990). This interpretation has three major implications for the palaeogeography of the Park Hill Member. First, it suggests that the ebb current flowed down a south-westward sloping shoreface, away from a shoreline situated farther to the north-east. Second, it suggests that the north-easterly current direction measured in the complex cross-bedded cosets was that of the flood tide. Third, it can be inferred that the east to east-south-east current directions measured for many of the trough cross-bedded sandstones represents the longshore current flow.

One of the rare mudstone beds in the Park Hill Member occurs above this bedding plane; it is overlain by plane-bedded sandstone and coarse-grained cross-bedded sandstone which may represent storm deposits.

Locality 2: Bedding plane exposure in Unit E, Park Hill Member. Shows in plan view, nests of trough cross-bedding interpreted as the truncated tops of sinuous-crested ripples formed in a south-easterly directed current. From the foregoing argument, such currents were oriented approximately perpendicular to the slope of the shoreface deduced at Locality 1, indicating a component of longshore sediment transport during deposition of these beds.

Between Localities 2 and 3, and farther to the south-east, many bedding planes show the marks of burrowing organisms. From this part of the succession, Brasier and Hewitt (1979) describe the trace fossils *Psammichnites*, *Neonereites*, *Arenicolites* and *Planolites,* with *Diplocraterion* added more recently (Brasier, written comm. 1990).

Locality 3: Further bedding plane exposure in Unit E. Shows asymmetric (current) ripples, with current direction to the south-west. Between Localities 3 and 4 can be observed further ripple markings and a system of northerly-trending ribs of problematic origin. Near Locality 4, large elliptical structures on the bedding plane were possibly produced by the escape of water during compaction of the sediments.

Locality 4: The contact between the Park Hill and Tuttle Hill Members is for convenience placed at the base of the prominent sheared mudstone bed (base of Unit G), though more accurately it is a sedimentological transition represented by Units F, G and H. The first indication of an environmental change is the incoming of a mudstone-thin sandstone sequence at the base of Unit F (top of the Park Hill Member). The mudstone at the base of Unit G represents significant flooding of the Cambrian shelf; the overlying sandstones are typically plane-bedded, show normal or reverse grading, or abrupt changes between texturally differing sandstone layers. They are interpreted as representing in part the deposits of sediment gravity flows induced by storm events acting on a shoreline that had receded as a result of renewed transgression.

The shearing seen in the Unit G mudstone occurred in a regime of north-eastwards directed compression during which most of the strain was concentrated along easily deformable sedimentary layers. The strike-slip faults seen on the bedding planes immediately to the north were probably lateral ramp structures belonging to this deformation. At least some of this shearing occurred during emplacement of the lamprophyre intrusions and is therefore of late Ordovician age.

Locality 5: Unit H contains some of the coarsest-grained sandstones in the Tuttle Hill Member. The main part of each bed is either massive or shows poorly-developed cross-bedding with foreset beds, where seen, inclined to the north-east. Many beds are modified at the top by cross-bedded sets indicative of a reversed, south-westwards current flow. A distinctive feature of Unit H is the occurrence of locally thick, highly lenticular packages of laminated mudstone and siltstone; mudstone also occurs as clasts above the erosive bases of many sandstone beds. The overall character of Unit H is suggestive of deposition within a storm-influenced offshore ridge system, as discussed in Part 1.

Locality 6: This locality marks the start of a traverse through Unit I of the Tuttle Hill Member. The beds in the lower part of the unit comprise thick packages of tabular-planar (locally trough) cross-bedded sandstone which alternate with compound-lenticular cross-bedded sandstone. In Part 1 it is suggested that the former represent sections through migratory sandwaves formed in a north-east directed current regime, whereas the latter are sections through sandwaves with scoured and megarippled tops formed in a more unsteady current regime. Following from this interpretation it may be inferred that the tabular-planar beds, belonging to larger and more simple sand bodies, were formed in deeper waters, with the compound-lenticular beds reflecting periods of shoaling to shallower water depths on the shelf. The compound-lenticular types show a heirarchy of low-order internal discontinuities, commonly outlined by trails of mudstone clasts, and resemble the Class V sandwaves of Allen (1980).

Mudatone forms ubiquitous drapes to the Unit I sandstone beds. The thicker mudstone intervals which separate the different sandstone packages were possibly deposited following minor flooding events which changed current paths on the shelf. Conditions of abundant arenaceous supply and ample water depths are suggested by the thickness of the tabular-planar beds (2m) in the vicinity of the two lamprophyre sheets (Figure 5); above this, the beds become thinner towards Unit J.

Locality 7: Beds of Unit J constitute a heterolithic (sandstone-mudstone) interval within the Tuttle Hill Member. The sandstones have parallel sides and show inverse or normal grading, the latter to ripple cross-laminated tops. Like the succession at the base of Unit G, these beds are suggested to represent deposition from storm-induced sediment gravity flows following a period of transgression that caused the shoreline to retreat landwards.

Locality 8: Unit K comprises a thick sequence of compound-lenticular cross-bedded sandstone, of subarkose or lithic subarkose composition. Some of these beds show normal grading to ripple-marked sandstone or siltstone tops, similar to sandstones of Unit J. Other beds are capped by poorly-sorted siltstone-sandstone layers containing mudstone rafts, possibly indicative of storm-reworking of bed tops. Most beds are similar to the sandstone packages near the base of Unit I and are probably sections through complex sandwaves formed during an extended interval of shoaling on the shelf.

Upwards through the Tuttle Hill Member, sandstones generally become finer-grained, more micaceous and darker maroon in colour. Green glauconite grains are conspicuous on weathered surfaces viewed by hand lens. Bioturbation of the muddy tops to the beds also becomes more developed up-section.

Locality 9: The sedimentary change to Unit L is remarkably sharp, the lenticular beds of the underlying sandstones giving way to a succession of maroon, glauconitic, micaceous subarkosic sandsones in beds which are perfectly flat-topped and parallel-sided throughout (Figure 2). Most beds show plane-lamination, or very low-angle cross-lamination. Mudstone drapes only sporadically occur but it is possible that the extensive bioturbation has homogenised the mudstone and sandstone components, at least in the upper parts of the beds. The interpretation of these beds is problematic; they may reflect a particularly extended period of storm-induced deposition on a part of the shelf situated close to an abundant supply of arenaceous material.

Locality 10: Sandstones of the Jee's Member comprise cosets of tabular-planar and trough cross-bedding, with some plane-bedded intervals. Winnowed lags sporadically occur along the bed tops. All these features indicate a greater degreee of exposure to wave and/or current action which is indicative of a general shoaling of the shelf to shallower water depths.

Brasier and Hewitt (1979) describe extensive bioturbation in this member, noting the presence of the trace fossils *Isopodichnus*, *Arenicolites*, *Planolites* and *Didymaulichnus* suggestive of the *'Cruziana* facies'.

Locality 11: This small outcrop of the Home Farm Member comprises red sandy limestones and phosphatized limestone conglomerates of the *Hyolithes* Limestone; the basal conglomerates which rest erosively on the Jee's Member occur nearby, but are not exposed here. Tubular fossils, representing *Hyolithellus*, *Coleoloides* and *Torellela* are easily distinguished in these beds; brachiopod remains also occur (for an extensive review and bibliography see Brasier, 1989).

Sedimentary discontinuities within this member are hardgrounds formed by successive episodes of marine erosion in an environment starved of arenaceous clastic material (Brasier and Hewitt, 1979). Such conditions are typical of those prevailing during the accumulation of condensed sections on marine flooding surfaces (e.g. Haq, 1991), and suggest that the Home Farm Member defines a major sequence boundary. This is in keeping with regional correlations (Brasier and others, 1992) showing that the disconformity at the member's base represents a sedimentary hiatus present throughout the Early Cambrian successions in England and Newfoundland.

Beds of the Woodlands Member are rather poorly exposed above this locality. They comprise dark grey, micaceous, glauconitic, subarkosic sandstones which commonly show a fine parallel internal lamination. Elsewhere in the quarry, these sandstones form thick beds with current-rippled topsurfaces. The upper 1.5m is bioturbated and calcareous, representing an interval of stillstand and sediment starvation that heralded deposition of the overlying Stockingford Shale Group.

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References

ALLEN, J R L. 1957. The Precambrian geology of Caldecote and Hartshill, Warwickshire. *Transactions Leicestershire Literary and Philosophical Society,* Vol.51, 16–31.

ALLEN, J R L. 1980. Sand waves: a model of origin and internal structure. *Sedimentary Geology,* Vol.26, 281–328.

BRASIER, M D. 1980. The Lower Cambrian transgression and glauconite-phosphate facies in western Europe. *Journal of the Geological Society,* Vol.137, 695–703.

BRASIER, M D. 1989. Sections in England and their correlation. 83–104 in *The Precambrian-Cambrian Boundary.* COWIE, J W and BRASIER, M D (editors). Oxford University Press.

BRASIER, M D, ANDERSON, M M and CORFIELD, R M. 1992. Oxygen and carbon isotope stratigraphy of early Cambrian carbonates in southeastern Newfoundland and England. *Geological Magazine,* Vol.129, 265–279.

BRASIER, M D, HEWITT, R A and BRASIER, C J. 1978. On the late Precambrian-early Cambrian Hartshill Formation of Warwickshire. *Geological Magazine,* Vol.115, 21–36.

BRASIER, M D and HEWITT, R A. 1979. Environmental setting fossiliferous rocks from the uppermost Proterozoic-Lower Cambrian of central England. *Palaeogeography, Palaeoclimatology and Palaeoecology,* Vol.27, 35–57.

BRIDGE, D McC, CARNEY, J N and LAWLEY, R S L. *In prep.* Geology of the country around Coventry. *Memoir of the British Geological Survey,* Sheet 169 (England and Wales).

CARNEY, J N. 1992. Geology and structure of the Lower Cambrian Hartshill Sandstone Formation: information from quarries north-west of Nuneaton. *British Geological Survey Technical Report,* WA/92/08.

CARNEY, J N. *In prep.* Geology and structure of Precambrian rocks in quarries northwest of Nuneaton. *British Geological Survey Technical Report.*

DALRYMPLE, R W. 1984. Morphology and internal structure of sandwaves in the Bay of Fundy. *Sedimentology,* Vol.31, 365–382.

EASTWOOD, T, GIBSON, W, CANTRILL, T C and WHITEHEAD, T H. 1923. The Geology of the country around Coventry. *Memoir of the British Geological Survey of England and Wales,* Sheet 169.

FISHER, R V. 1961. Proposed classification of volcaniclastic rocks. *Geological Society of America Bulletin,* Vol.72, 1409–1414.

FISHER, R V. 1984. Submarine volcaniclastic sediments and rocks. 5–27 in *Marginal Basin Geology.* KOKELAAR, B P and HOWELLS, M F (editors). Geological Society Special Publication, No.16.

FISKE, R S and MATSUDA, T. 1964. Submarine equivalents of ash flows in the Tokiwa Formation, Japan, *American Journal of Science,* Vol.262, 76–106.

FORD, T D. 1958. Pre-Cambrian fossils from Charnwood Forest. *Proceedings Yorkshire Geological Society,* Vol.31, 211–217.

GHIBAUDO, G. 1992. Subaqueous sediment gravity flows: practical criteria for their field description and classification. *Sedimentology,* Vol.39, 423–454.

HAINS, B A and HORTON, A. 1969. *British Regional Geology. Central England* (3rd Edition). (London: HMSO for Institute of Geological Sciences)

HAQ, B U. 1991. Sequence stratigraphy, sea-level change, and significance for the deep *sea. Special Publication International Association of Sedimentologists,* Vol.12, 3–39.

HEIN, F J, ROBB, G A, WOLBERG, A C and LONGSTAFFE, F J. 1991. Facies descriptions and associations in ancient reworked (?transgressive) shelf sandstones: Cambrian and Cretaceous examples. *Sedimentology,* Vol.38, 405–431.

HISCOTT, R N and MIDDLETON, G V. 1979. Depositional mechanics of thick-bedded sandstones at the base of a submarine slope, Tourelle Formation (Lower Ordovician), Quebec, Canada. *Special Publication Society of Economic Palaeontologists and Mineralogists,* Vol.27, 307–326.

HOWELL, H H. 1859. The Geology of the Warwickshire Coalfield. *Memoir of the Geological Survey of England and Wales.*

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

LAPWORTH, C. 1886. On the sequence and systematic position of the Cambrian rocks of Nuneaton. *Geological Magazine,* Vol.3, 319–322.

LAPWORTH, C, WATTS, W W and HARRISON, W J. 1898. Sketch of the geology of the Birmingham District. *Proceedings of the Geologists Association,* Vol.15, 313–389.

LOWE, D R. 1982. Sediment gravity flows: II. depositional models with special reference to the deposits of high-density turbidity currents. *Journal of Sedimentary Petrology,* Vol.52, 279–297.

McFARLANE, M J. 1983. A low level laterite profile from Uganda and its relevance to the question of parent material influence on the chemical composition of laterites. 69–76 in *Residual deposits: surface related weathering processes and materials.* WILSON, R C L (editor). Geological Society Special Publication, No.11.

McKERROW, W S, SCOTESE, C R and BRASIER, M D. 1992. Early Cambrian continental reconstructions. *Journal of the Geological Society,* Vol.149, 599–606.

MOLYNEUX, S G. 1992. A palynological investigation of samples from the Hartshill Quartzite Formation, Nuneaton area (1:50 000 Sheet 169, Coventry). *British Geological Survey Technical Report,* WH/92/210R.

OLD, R A, HAMBLIN, R J 0, AMBROSE, K and WARRINGTON, G. 1991. Geology of the country around Redditch. *Memoir of the British Geological Survey,* Sheet 183 (England and Wales).

MOSELEY, J and FORD, T D. 1985. A stratigraphic revision of the Late Precambrian rocks of the Charnwood Forest, Leicestershire. *Mercian Geologist,* Vol.10, No.1, 1–18.

PHARAOH, T C, WEBB, P C, THORPE, R S and BECKINSALE, R D. 1987. Geochemical evidence for the tectonic setting of late Proterozoic volcanic suites in central England. 541552 *in Geochemistry and Mineralization of Proterozoic Volcanic Suites,* Geological Society Special Publication, No.33.

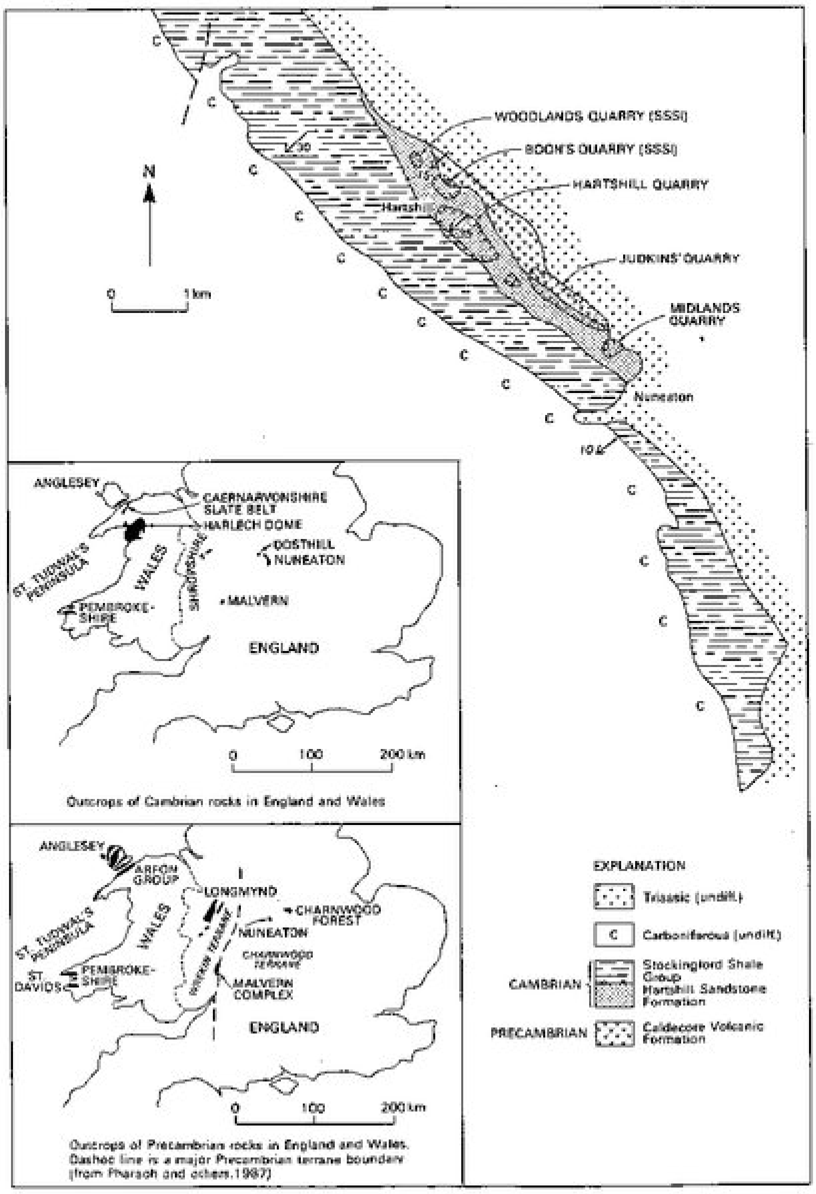
SIMPSON, E L and ERIKSSON, K A. 1990. Early Cambrian progradational and transgressive sedimentation patterns in Virginia: an example of the early history of a passive margin. *Journal of Sedimentary Petrology,* Vol.60, 84–100.

TUCKER, R D and PHARAOH, T C. 1991. U-Pb zircon ages for Late Precambrian igneous rocks in southern Britain. *Journal of the Geological Society,* Vol.148, 435–443.

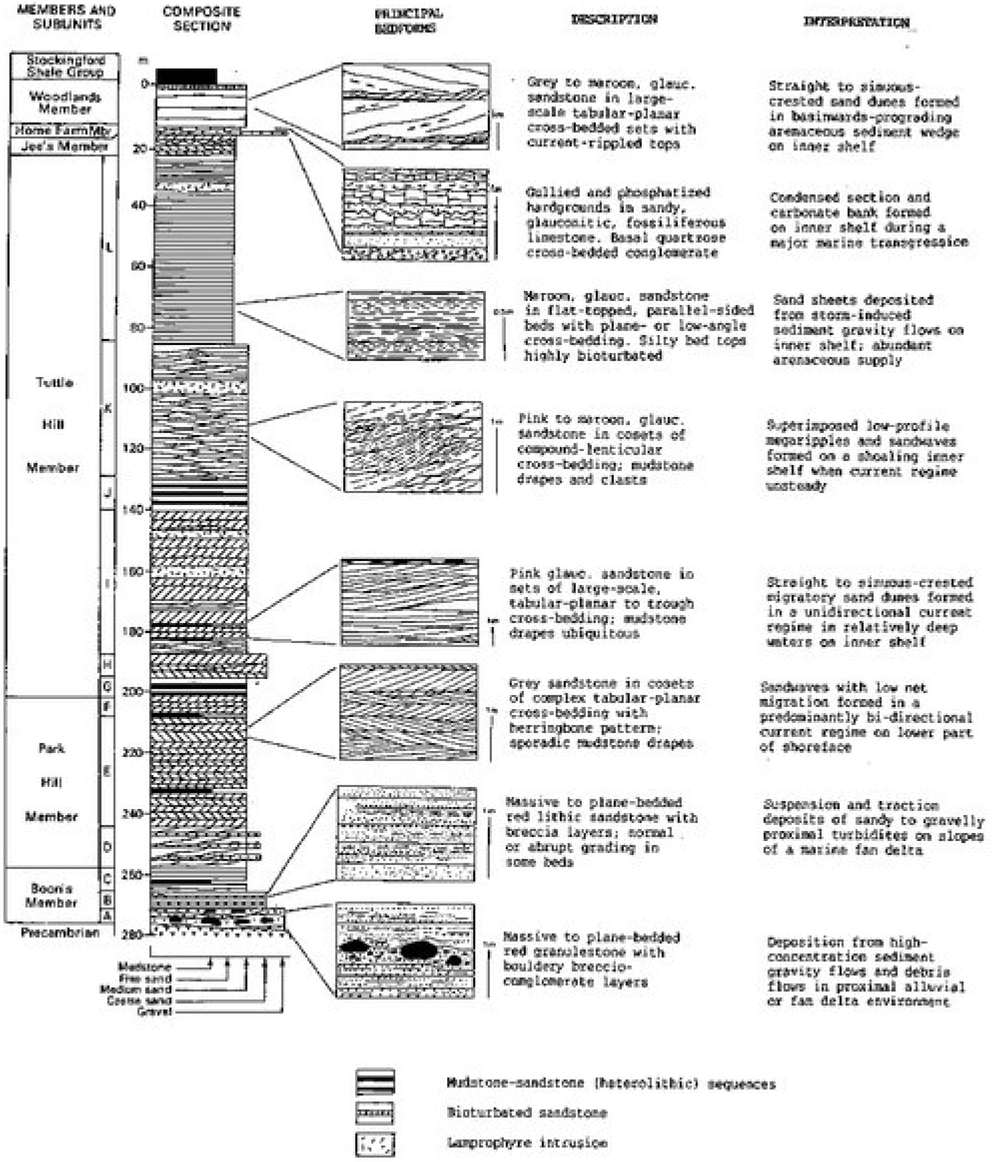
WALKER, R G. 1978. Deep water sandstone facies and ancient submarine fans: models for stratigraphic traps. *American Association of Petroleum Geologists Bulletin,* Vol.62, 932966.

WILSON, J T. 1966. Did the Atlantic close and then re-open? *Nature,* Vol.211, 676–681.

WORSSAM, B C and OLD, R A. 1988. Geology of the country around Coalville. *Memoir of the British Geological Survey, Sheet* 155 (England and Wales).

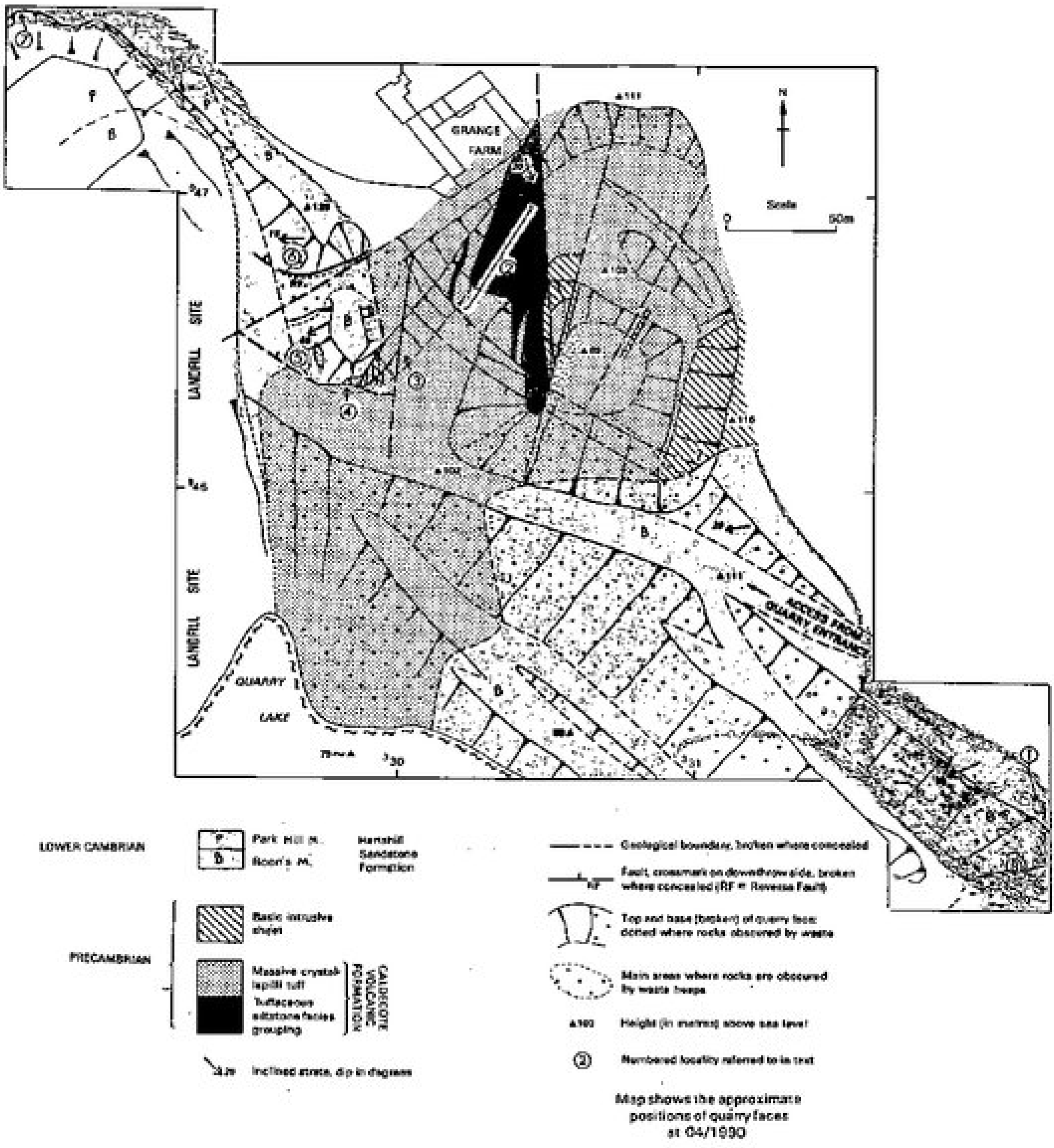


(Figure 1) Regional and local geological setting of the Nuneaton Inlier.

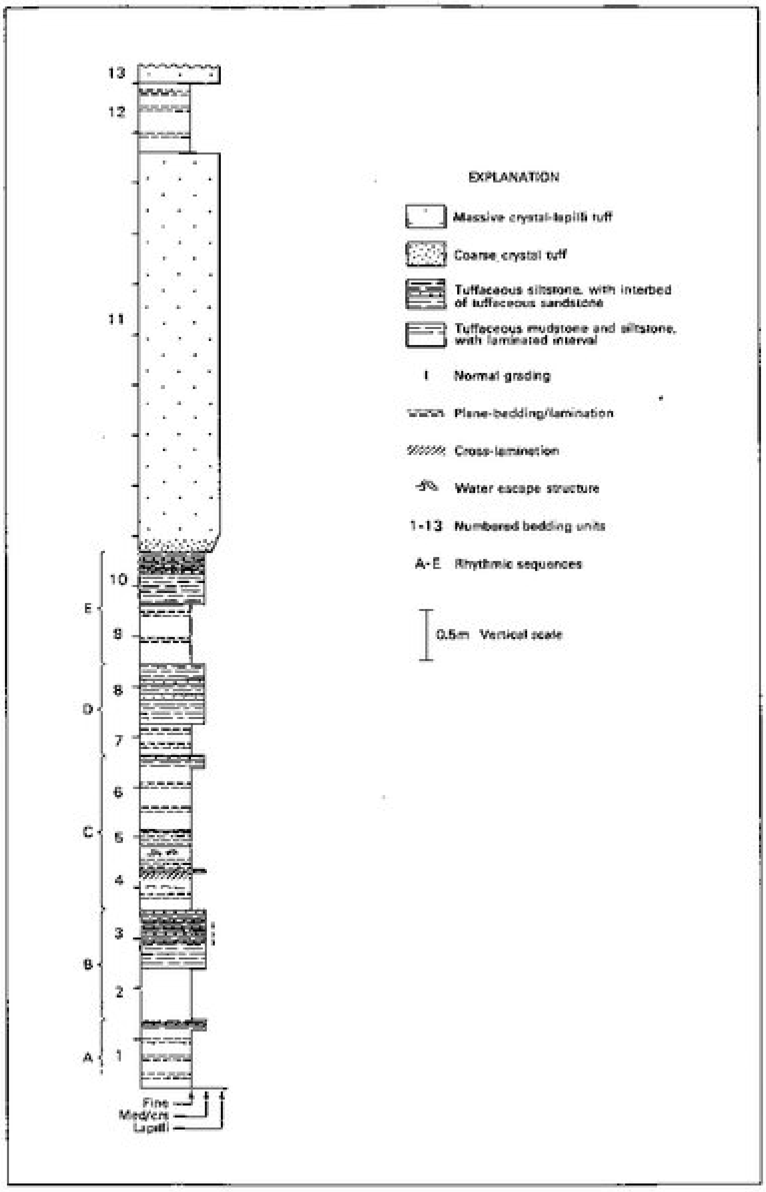


DESCRIPTION	INTERPRETATION
Grey to maroon, glauc. sandstone in large-scale tabular-planar cross-bedded sets with current-rippled tops	Straight to sinuous-crested sand dunes formed in basinwards-prograding arenaceous sediment wedge on inner shelf
Gullied and phosphatized hardgrounds in sandy, glauconitic, fossiliferous limestone. Basal quartzose cross-bedded conglomerate	Condensed section and carbonate bank formed on inner shelf during a major marine transgression
Maroon, glauc. sandstone in flat-topped, parallel-sided beds with plane- or low-angle cross-bedding. Silty bed tops highly bioturbated	Sand sheets deposited from storm-induced sediment gravity flows on inner shelf; abundant arenaceous supply
Pink to maroon, glauc. sandstone in cosets of compound-lenticular cross-bedding; mudstone drapes and clasts	Superimposed low-profile megaripples and sandwaves formed on a shoaling inner shelf when current regime unsteady
Pink glauc. sandstone in sets of large-scale, tabular-planar to trough cross-bedding; mudstone drapes ubiquitous	Straight to sinuous-crested migratory sand dunes formed in a unidirectional current regime in relatively deep waters on inner shelf
Grey sandstone in cosets of complex tabular-planar cross-bedding with herringbone pattern; sporadic mudstone drapes	Sandwaves with low net migration formed in a predominantly bi-directional current regime on lower part of shoreface
Massive to plane-bedded red lithic sandstone with breccia layers; normal or abrupt grading in some beds	Suspension and traction deposits of sandy to gravelly proximal turbidites on slopes of a marine fan delta
Massive to plane-bedded red granulestone with bouldery breccio-conglomerate layers	Deposition from high-concentration sediment gravity flows and debris flows in proximal alluvial or fan delta environment

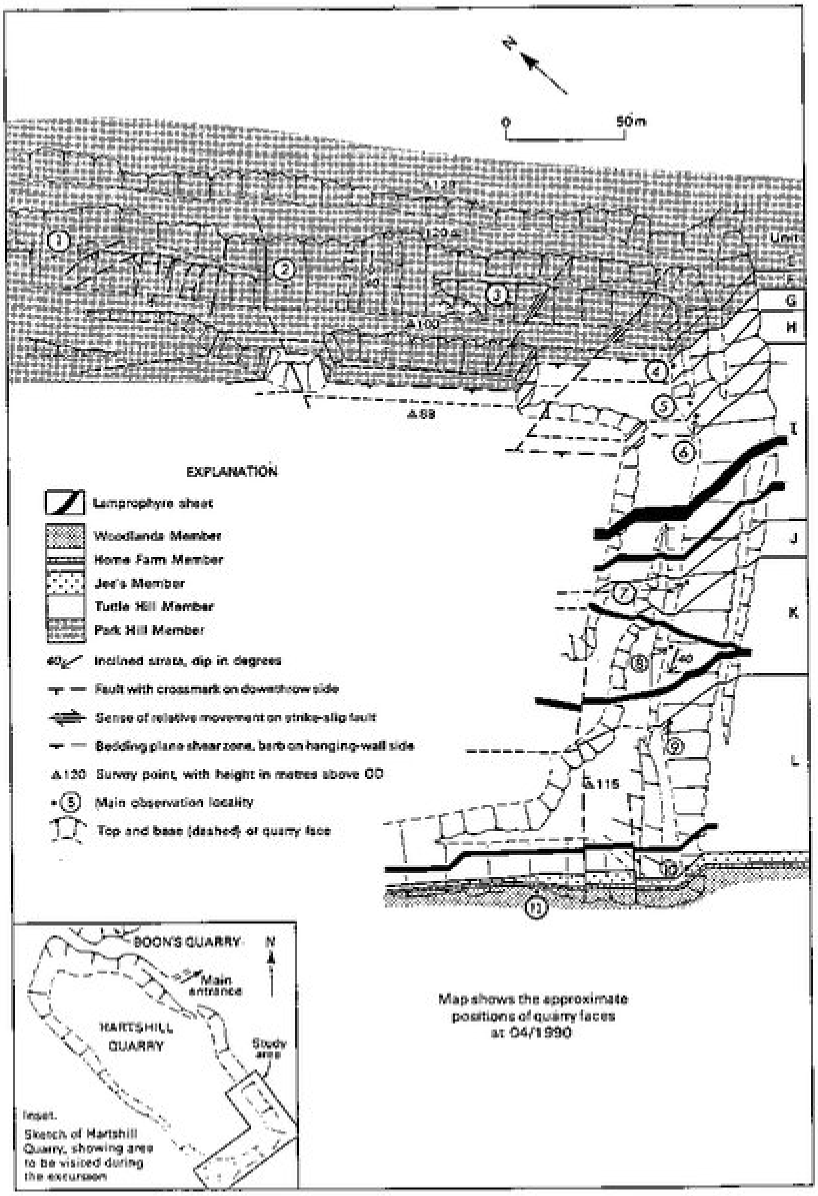
(Figure 2) Composite stratigraphic column in the Hartshill Sandstone Formation, showing the principal lithofacies and their interpretation.



(Figure 3) Geological sketch map of the northern part of Boon's Quarry. The SSSI extends along the quarry face between Localities 2 and 7.



(Figure 4) Section in the Caldecote Volcanic Formation at the SSSI in Boon's Quarry (Locality 2, (Figure 3)).



(Figure 5) Geological sketch map of the south-eastern part of Hartshill Quarry.