Precambrian Rocks of England and Wales

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British Geological Survey

Chapter 3

Nuneaton Inlier

INTRODUCTION

J. N. Carney

The Precambrian outcrop at Nuneaton is limited to a 2.8 km[2] area, but quarrying has revealed a number of impressively large sections that allow a comprehensive range of lithologies and structures to be viewed. To take advantage of this, and of current local conservation initiatives, two sites are described, the existing GCR site in Boon's Quarry and a new site at nearby Judkins' Quarry (Figure 3.1). Taken together, these sites show that the larger part of the Precambrian succession consists of bedded volcaniclastic rocks collectively known as the Caldecote Volcanic Formation. They also demonstrate a complex late Precambrian history, involving faulting, flexuring and two phases of igneous intrusion, which took place before deposition of the overlying and unconformable Lower Cambrian strata. The Caldecote Volcanic Formation and associated intrusions can be compared geochemically, if not always lithologically, with the Precambrian rocks of Charnwood Forest, some 23 km farther to the north-east (Carney and Pharaoh, 1993; Bridge *et al*., 1998), as discussed in the introduction to Chapter 2. It follows that the two Precambrian sequences are correlatives, and together form a major basement domain known as the 'Charnwood Terrane' (Chapter 1).

Lapworth (1882) first demonstrated the antiquity of the Caldecote Volcanic Formation, by his discovery of Cambrian fossils in the strata lying unconformably above. However, their Precambrian age was not finally confirmed until Lapworth (1898) established the magnitude of the unconformity, from the fact that the highest beds in the overlying Hartshill Sandstone Formation contain Lower Cambrian fossils. The exposures of this unconformable contact, which is particularly accessible at Boon's Quarry, underline the importance of the Nuneaton Inlier. This is one of the few localities in southern Britain with rocks that demonstrate the passage between the Proterozoic and Lower Palaeozoic erathems.

The early work of Lapworth (1886, 1898) recognized the diversity of lithologies in the then 'Caldecote Volcanic Series'. Subsequent studies

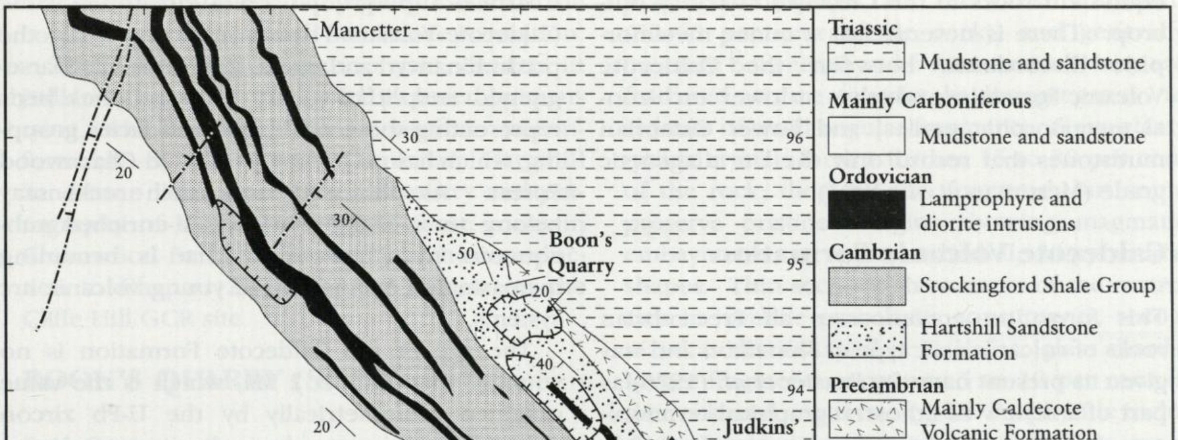

Figure 3.1 Outline geological map of part of the Nuneaton Inlier, showing the location of the GCR sites (in bold lettering).

involved petrographical and chemical investigations into a body of granophyric diorite at Judkins' Quarry, which represents the final phase of Precambrian magmatism. The classification of this intrusion as 'markfieldite' by Jones (1935) was in recognition of its similarity to the eponymous intrusive rocks in the south of Charnwood Forest (Chapter 2). At the time, this correlation was highly significant to the Precambrian stratigraphy of the English Midlands because the quarry exposures clearly demonstrate that the granophyric diorite is overlain unconformably by Lower Cambrian strata (Wills and Shotton, 1934). Hence the Charnwood Forest markfieldite, and the strata into which it was emplaced, must also be Precambrian. The studies by Allen (1957, 1968a) were the most modern treatments of the stratiform Caldecote Formation sequences and their interpretation, until the work carried out by Carney and Pharaoh (1993), Carney (1995) and Bridge *et al.* (1998).

Although the Nuneaton Precambrian rocks were affected by late Precambrian folding and faulting, and are also well jointed, they do not show the penetrative cleavage affecting the equivalent rocks in the Charnwood Forest outcrop. There is nevertheless a minor metamorphic discordance between the Caldecote Volcanic Formation, which is at lower anchizonal metamorphic grades, and Lower Cambrian mudstones that record only the late diagenetic grade (Merriman *et al.*, 1993).

Caldecote Volcanic Formation

This formation encompasses all Precambrian rocks of volcaniclastic type at Nuneaton and was given its present name by Brasier *et al.* (1978) as part of a review of lithostratigraphical terminology for the overlying and unconformable Hartshill Sandstone Formation. Its type area is considered to be the whole of the Precambrian outcrop shown in Figure 3.1, and the type section (Bridge *et al.*, 1998) has been chosen as the Boon's Quarry GCR site. The formation is estimated to be at least 130 m thick beneath the unconformable Lower Cambrian and Triassic strata and its base is neither seen nor has been encountered in boreholes.

The Caldecote Formation is informally subdivided (Bridge *et al.*, 1998) into two principal components; a crystal-lapilli tuff facies grouping, which is predominant, and a bedded to laminated, tuffaceous siltstone facies grouping. The finer-grained lithologies constituting the latter grouping were originally thought to represent a lower bedded succession (Allen, 1968a), but the present, particularly deep, quarry sections demonstrate that in fact they are interspersed at various stratigraphical levels within the crystal-lapilli tuffs. The sequence in the quarries has a remarkably high content of pyroclastic material and so may be the approximate equivalent of the Maplewell Group in Charnwood Forest (Chapter 2).

Geochemical studies summarized by Carney and Pharaoh (1993) and Bridge *et al.* (1998) concluded that the Caldecote Volcanic Formation represents volcaniclastic sediments containing detritus derived from similar magmatic sources to those supplying the Charnian Supergroup farther north. A volcanic arc founded upon oceanic or attenuated continental crust is therefore the most likely environment in which these rocks could have formed (Chapter 2, Introduction). Sedimentary structures such as normal grading and soft sediment deformation suggest subaqueous deposition of the Caldecote Volcanic Formation, as is the case for the Charnian Supergroup. Unique features of the Caldecote Volcanic Formation, however, are the predominance, and great thickness, of coarse-grained and lithologically homogeneous beds representing the crystal-lapilli tuff facies grouping, which has no precise parallel in Charnwood Forest. As discussed later, such rocks may belong to a category of crystal-enriched subaqueous pyroclastic flow that is becoming increasingly documented in young volcanic arc systems.

The age of the Caldecote Formation is no younger than 603 ± 2 Ma, which is the value obtained radiometrically by the U-Pb zircon method on the granophyric diorite intrusion at Judkins' Quarry (Tucker and Pharaoh, 1991). This limiting age for the Caldecote Formation has also been applied to the Charnian Supergroup, on the basis of geochemical similarities, discussed above, between the Nuneaton granophyric diorite and the markfieldite intrusion (South Charnwood Diorites) of Charnwood Forest. Such a correlation presents problems, however, since the Charnian Supergroup contains Ediacaran fossils (Chapter 8), the presence of which in other parts of the world would indicate an age no older than 580 Ma (see discussion in McIlroy *et al.*, 1998, and Chapter 2).

Precambrian intrusive rocks

Intermediate to basic intrusions are an important feature of the Nuneaton Precambrian assemblage, and occupy an estimated 25 per cent by volume of the total Precambrian exposure at the large Judkins' Quarry GCR site. Two separate intrusive phases are demonstrated by cross-cutting relationships seen here; they comprise an early complex of porphyritic to sparsely-phyric basaltic-andesite and microdiorite intrusions, and a younger intrusive stock of granophyric diorite (or markfieldite).

The basaltic-andesite and microdiorite intrusions were collectively termed the 'Blue Hole Intrusive Series' by Allen (1957), but such a rank is inappropriate for these rocks, which are here referred to informally on the basis of lithological type. These intrusions are chemically identical to the coarser-grained 'North Charnwood Diorites' of Charnwood Forest (Bridge *et al.*, 1998). Their Precambrian age is demonstrated, uniquely in the Midlands region, at the Boon's Quarry GCR site, which shows that a dyke of basaltic-andesite, emplaced into crystal-lapilli tuff, becomes reddened in its upper part and is unconformably overlain by basal beds of the Lower Cambrian Hartshill Sandstone Formation.

The intrusion of granophyric diorite in Judkins' Quarry has been well exposed by quarrying, which shows it to be overlain unconformably by the Lower Cambrian Hartshill Sandstone Formation. The chemistry and petrography of the equivalents of these rocks in Charnwood Forest is discussed in the introduction to Chapter 2, and in the section on the Cliffe Hill GCR site.

BOON'S QUARRY (SP 329 947)

J. N. Carney

Introduction

The highly accessible exposures of Precambrian and Cambrian rocks make the Boon's Quarry GCR site (Figure 3.2) one of the classic sites of British stratigraphy. In recognition of its importance, the quarry face immediately below (to the south of) Grange Farm has been designated the type section for the diverse volcaniclastic sequence constituting the Caldecote Volcanic Formation (Bridge *et al.*, 1998). Many photographical illustrations of the various lithologies are given in Carney and Pharaoh (1993) and Bridge *et al.* (1998), who also document the petrography, chemistry and mode of origin of these rocks in some detail. A further outstanding feature of this site is the exposure of the base-Cambrian unconformity (Figure 3.3), which preserves on the Precambrian rocks, a reddened, spheroidally-weathered profile (e.g. Brasier and Hewitt, 1979; Carney, 1995; Bridge *et al.*, 1998). The unconformity truncates a basaltic-andesite dyke, proving the latter's Precambrian age.

Description

The two informal subdivisions of the Caldecote Formation, discussed in the introduction to Chapter 3, are well represented at this site and their distribution is shown in Figure 3.2.

The crystal-lapilli tuff facies grouping equates to the feldspar–quartz–crystal-tuff (Welded Tuff) category of Allen (1957) and to the quartz–felsite of Lapworth (1882). A commonly massive internal appearance, coarse grain size and crystal-rich composition are distinctive features of this facies, which occupies most of the Precambrian outcrop at the site. White to pale pink or grey plagioclase crystals are the most abundant (50–60 per cent of the rock), and generally measure between 2 and 6 mm across. Many are fractured, or are completely disaggregated to clusters of small angular fragments. Grey, glassy quartz crystals form a further 15 to 20 per cent of the rock; they are also fractured, but some preserve pristine margins showing magmatic embayments, or have euhedral, bi-pyramidal shapes. Thin sections show areas of the matrix rich in juvenile pyroclastic constituents, recognized as sliver-shaped or reticulate glass shards. Larger fragments constitute 5 to 10 per cent of the rock, and are of two types. Porphyritic inclusions up to several centimetres in size were noted by Waller (1886) and Allen (1957). They have ovoid, discoid or equidimensional shapes, and commonly have ragged, sharply angular margins with the enclosing crystal-lapilli tuff. Their fine-grained matrix encloses plagioclase and quartz crystals of a similar size and composition to those in the host rock, although not as abundant. Lithic blocks commonly have sharp, angular margins against the host tuff; they include fine-grained aphyric to sparsely porphyritic andesite or dacite, devitrified glass with relict perlitic texture and welded tuff with fluidal textures.

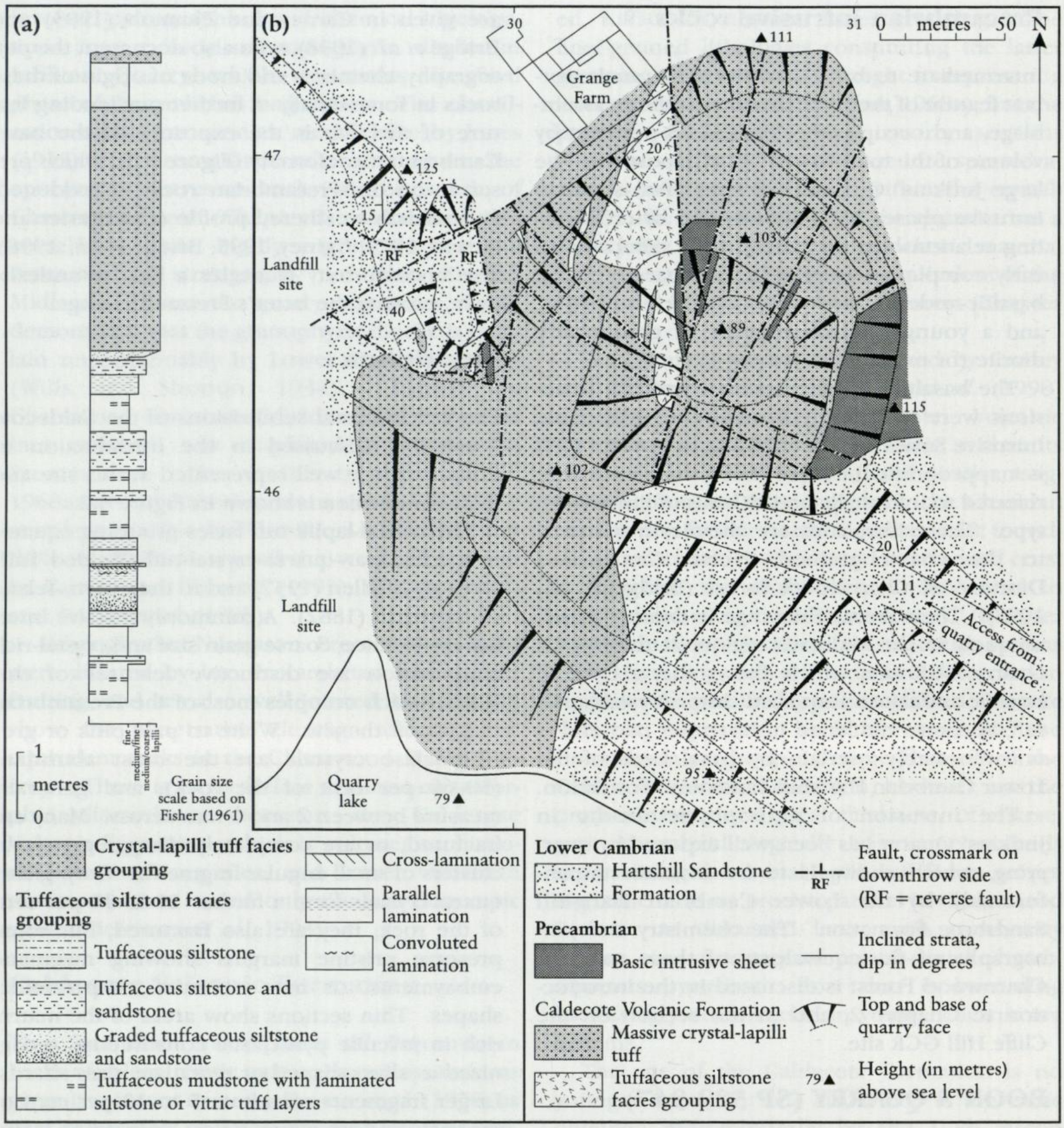

Figure 3.2 Geological map of the northern part of Boon's Quarry (from Bridge *et al.*, 1998). The column on the left is a composite section measured on the upper and lower quarry faces, immediately south of Grange Farm.

The tuffaceous siltstone facies grouping is at least 5.5 m thick at the type section (Figure 3.2). It has a characteristic parallel stratification picked out by pale grey, dark grey and olive-green weathering tints, and is made up of regular alternations that define a series of upwards-coarsening cycles, the stratigraphically highest culminating in about 4 m of crystal-lapilli tuff. The mudstone component appears massive or only faintly laminated, but in polished slabs it commonly shows an intensely convoluted silty lamination. In thin sections the more silty laminae contain abundant sliver-shaped microcrystalline aggregates representing devitrified glass shards. Tuffaceous siltstone beds have a millimetre-scale parallel lamination, which is in places deformed into domical structures. Low-angle planar cross-lamination is more rarely seen, in one case giving a current flow almost due south. In thin sections the siltstone laminae

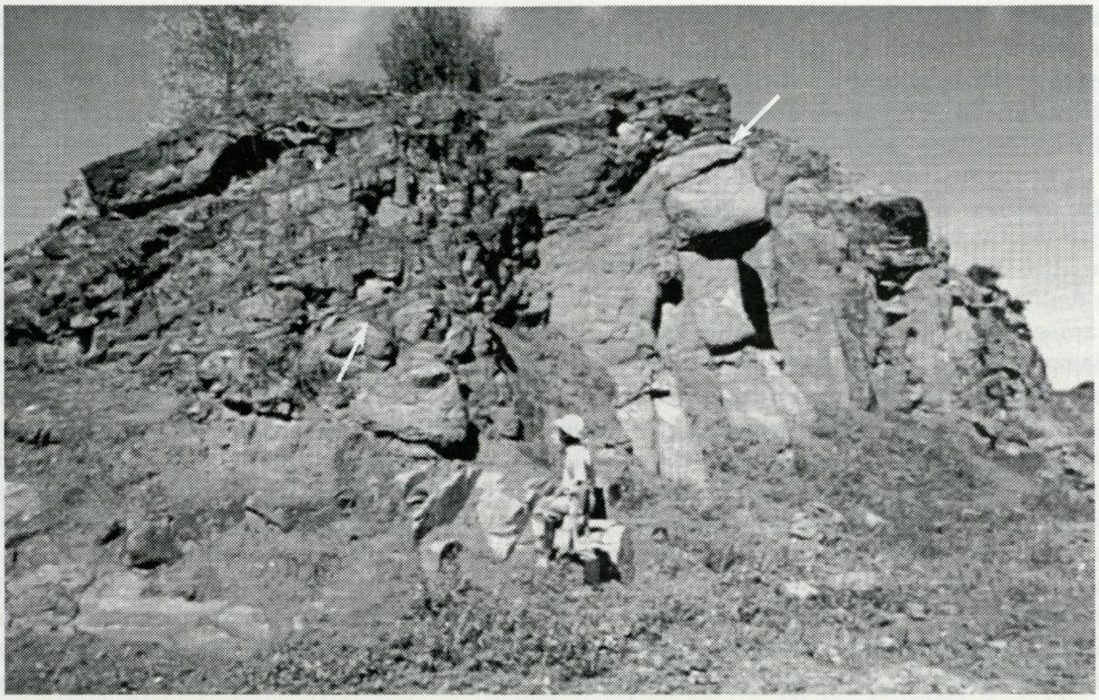

Figure 3.3 The Precambrian–Cambrian unconformity (arrowed) at Boon's Quarry. Spheroidally weathered Precambrian crystal-lapilli tuff of the Caldecote Volcanic Formation is overlain by redbeds of the Boon's Member, basal to the Lower Cambrian Hartshill Sandstone Formation. (Photo: A14973, reproduced by kind permission of the Director, British Geological Survey, © NERC.)

are either crystal-enriched or composed of vitric tuff crammed with Y-shaped devitrified glass shards up to 1 mm in size. Tuffaceous sandstone beds are 5 to 20 mm thick; their bases are sharp and in places show erosion or are loaded into underlying mudstone. Normal grading is very common, and results in repetitively graded sequences, of sandstone passing up to siltstone and mudstone, representative of the 'Bouma' *b–e* turbidite divisions (Bouma, 1962).

The basaltic-andesite sheet truncated by the unconformity at Boon's Quarry is 3 m thick and composed of a fine-grained, dark green-grey rock. Its top becomes reddened within a few metres of the base of the Precambrian–Cambrian unconformity.

In keeping with the Precambrian sequences of the Nuneaton inlier, the rocks at Boon's Quarry show no evidence for penetrative cleavage deformation. There are, however, coarse sub-vertical joint sets, with a 1 m spacing, developed in the eastern wall of the small pit at the type section.

Interpretation

The Caldecote Volcanic Formation is, in terms of its grain size, a markedly diverse lithological association, although beds of the crystal-lapilli tuff facies are dominant. These lithologies are extremely coarse-grained and of 'proximal' aspect, but they were evidently deposited within a basin that was accumulating finer-grained and more distal sediments, represented by the tuffaceous siltstone facies grouping. Deposition of all of these strata in standing water is suggested by the presence of graded bedding, domical lamination indicative of liquefaction and possibly water-escape, convolute lamination and cross-lamination in the tuffaceous siltstone grouping. Moderate to deep-water conditions that were well below wave-base are further indicated by the absence of wave or tidal current-generated sedimentary structures. In keeping with this type of environment are features such as repetitive normal grading, interpreted to indicate deposition from distal, high-density turbidity currents (Lowe, 1982). The upwards-coarsening sedimentary cycles may have formed at times of progressively increasing seismic and/or eruptive activity, when rapidly accumulated material sloughed off the flanks of the volcanic axis. Glass shards that are locally concentrated in siltstone laminae testify to contemporary pyroclastic activity in the source region(s) of the volcanic arc (see 'Introduction', this chapter). Such beds are the deposits of ash falls into water, followed by reworking by bottom currents to form the characteristic laminated and cross-laminated structures.

Rocks of the crystal-lapilli tuff facies grouping are both conformable and intimately layered with the tuffaceous siltstone beds at the nearby Judkins' Quarry site, and therefore were similarly deposited under water. Their relatively constant crystal proportions, of about 55 per cent plagioclase and 20 per cent quartz, indicates a strong source control over their composition and suggests that most beds are compositionally immature. This is also indicated by the lack of abrasion of the crystals and delicate preservation of juvenile pyroclastic material, seen as glass shards in the matrix. These tuffs are possibly the products of pyroclastic eruptions derived from phenocryst-rich dacitic magmas (Bridge *et al.*, 1998). Previous workers suggested that they were welded tuffs (Allen, 1957, 1968a); however, although welding and plastic deformation is seen in some of the included blocks, true matrix shards are generally little-deformed and mainly show random orientation, arguing against welding on a significant scale after deposition. They are probably not welded tuffs as considered by Wright *et al.* (1980), but more resemble a category of subaqueous pyroclastic flow that has been described in basins marginal to volcanic arcs (Fiske and Matsuda, 1964). Such flows are viewed as having originated either from submarine eruptions, or from subaerial pyroclastic flows that subsequently entered water (see discussions in Fisher, 1984, and Stix, 1991). Crystal enrichment processes can operate in conjunction with this type of activity (Cas and Wright, 1987), but the large size of the crystals also indicates that the parental material was initially highly porphyritic.

Later in the arc's evolution the magmas became more basic and were introduced as basaltic-andesite sheets. These are the chemical equivalents of the North Charnwood Diorites (Carney and Pharaoh, 1993; Bridge *et al.*, 1998), and like the rest of the Caldecote Formation they were emplaced within a relatively juvenile arc.

Conclusions

Boon's Quarry occupies a small area but its accessibility, and the representative nature of the lithologies that are exposed, justify its selection both as a GCR site and the type section for the Caldecote Volcanic Formation. Sedimentary structures in the tuffaceous siltstone facies grouping indicate subaqueous deposition at moderate depths (at least) by a combination of turbidity current activity and the direct fall-out of fine ash. This fine-grained sedimentation either took place at some distance from the active volcanoes, or reflects times of relative quiescence. The crystal-lapilli tuff facies grouping, in contrast, is extremely coarse-grained and its remarkable uniformity of appearance, combined with its abundance of juvenile pyroclastic material (euhedral and shattered crystals, glass shards), suggests that it may have been generated by highly explosive, large-volume eruptions followed by subaqueous flowage of the ejected material. Basaltic dykes were then intruded as a prelude to magmatic cessation. The Precambrian rocks were later uplifted and eroded, and the remnant of a former spheroidal weathering profile on these rocks is uniquely preserved just below the unconformity overlain by Lower Cambrian strata.

JUDKINS' QUARRY (SP 345 934)

POTENTIAL GCR SITE

J. N. Carney and T. C. Pharaoh

Introduction

Judkins' Quarry has been proposed as a GCR site because it contains the largest and most comprehensive exposure anywhere in the Caldecote Volcanic Formation. The volcaniclastic lithologies exposed here (Figure 3.4) are more diverse than those seen at the formation's type section, in the Boon's Quarry GCR site, allowing a better appreciation of their mode of origin (e.g. Bridge *et al.*, 1998).

The site additionally represents the type locality for Precambrian intrusive activity in the Charnwood Terrane (Chapter 1), with all of the varieties discussed in the introduction to this chapter on view. F. Jones, who realized that it was unconformably overlain by Lower Cambrian strata, discovered the largest of these intrusions in 1932. The intrusion was named 'granophyric diorite' by Wills and Shotton (1934), who compared it to the 'markfieldite' of Charnwood Forest (see the Cliffe Hill GCR site report, Chapter 2), thereby inferring for the first time the latter's Precambrian age. The chemical similarities between the Judkins' granophyric diorite and markfieldite were soon realized (Jones, 1935), and have been confirmed by recent studies utilizing both major and trace elements (Carney and Pharaoh, 1993; Bridge *et al.*, 1998). These correlations between the Nuneaton and Charnwood Forest basement sequences now have an added significance because the Judkins' granophyric diorite is the only representative of the Charnwood Terrane to have had its age determined precisely by the U-Pb zircon method. The age obtained, of 603 ± 2 Ma (Tucker and Pharaoh, 1991), is the minimum for deposition of the Caldecote Volcanic Formation, although its relevance to the age of the Charnian Supergroup in Charnwood Forest is challenged by palaeontological evidence, as discussed in the introduction to this chapter.

Many of the faults shown in Figure 3.4 terminate at the base-Cambrian unconformity. The site is therefore of fundamental importance for unravelling the late Precambrian sequence of extrusion, intrusion and faulting in this sector of the Charnwood Terrane.

The Precambrian–Cambrian unconformity is a further major feature of this site, although it is unlike that at Boon's Quarry, being characterized by gullying and erosion rather than by weathering (e.g. Allen, 1968b; Bridge *et al.*, 1998). The site also exposes cross-sections through Trias-filled valleys eroded in the Precambrian surface.

Description

The site contains the two broad subdivisions of the Caldecote Volcanic Formation found in Boon's Quarry, to which the reader is referred for description. The crystal-lapilli tuff facies grouping forms most of the Precambrian exposure at the north-western end of the quarry (Figure 3.5) and is volumetrically the most important lithological division, amounting to about 85 per cent of the quarry exposures. Measured vertical sections through the Judkins' sequence shows that crystal-lapilli tuff can form massive beds up to 50 m thick.

Important sections showing the stratified top of a decimetres-thick crystal-lapilli tuff bed are displayed at Locality 1 (Figure 3.4). The lower stratified bed consists of lapilli tuff-breccia, about 12 m thick, characterized by about 25 per cent of dark grey to black porphyritic inclusions; some of these exhibit contorted or hooked shapes, and in certain layers they amalgamate to form discontinuous beds. The upper stratified bed, 10 m thick, is better-sorted and composed of centimetres-scale alternations between pale grey, coarse-grained crystal tuff and darker grey or greyish green crystal-vitric lapilli tuff. The latter is crammed with vitroclasts, 3 to 7 mm in size, with filamentous matrix textures, that enclose large quartz and plagioclase crystals with magmatically-embayed boundaries.

Large-scale disruption of bedding within the Caldecote Volcanic Formation is suggested by the sediment-raft breccias in the north-western part of Judkins' Quarry (e.g. Locality 2). These beds occur over at least 200 m of strike length; they contain metres-long rafts of laminated tuffaceous siltstone, some with ragged or feathered lateral terminations suggesting that they represent beds that were pulled apart within the enclosing tuff.

A further stratified variant of crystal-lapilli tuff is exposed beneath the Triassic unconformity in the central north-eastern face of Judkins' Quarry (Locality 3). It displays alternating crystal-dominant and lithic-dominant layers, and in thin section many of the lithic fragments are seen to be composed of devitrified and recrystallized volcanic glass, preserving relict perlitic textures. This lithology also encloses elongated, 10–40 mm size, dark maroon inclusions oriented parallel to local bedding planes; in a thin section they have fluidal textures resembling the fiamme of welded tuffs. Lower in the same section, beds of stratified and graded crystal-vitric tuff are apparently of basic composition; they contain abundant dark maroon, vesicular vitroclasts and fragments of dark brown, oxidized tachylyte glass, and there are no quartz crystals.

Representatives of the tuffaceous siltstone facies grouping occur at a few stratigraphical levels but are most prominent within a 7 m-thick series of beds, which can be followed for about 300 m along the north-eastern quarry face (e.g. at Locality 4). Descriptions of 'Bedded Tuffs' by Allen (1957), and of similar sequences by Lapworth (1886) and Wills and Shotton (1934), were based on earlier sections opened near here. The sequence locally contains green, laminated, fine-grained tuffs in beds up to 2 m thick. Thin sections show that these are vitric tuffs, crammed with devitrified glass shards showing sliver, crescentic, bubble-wall and Y-shapes. Accretionary lapilli, up to 4 mm in size, were found along a lamina plane in tuffaceous siltstone from the uppermost northern levels of

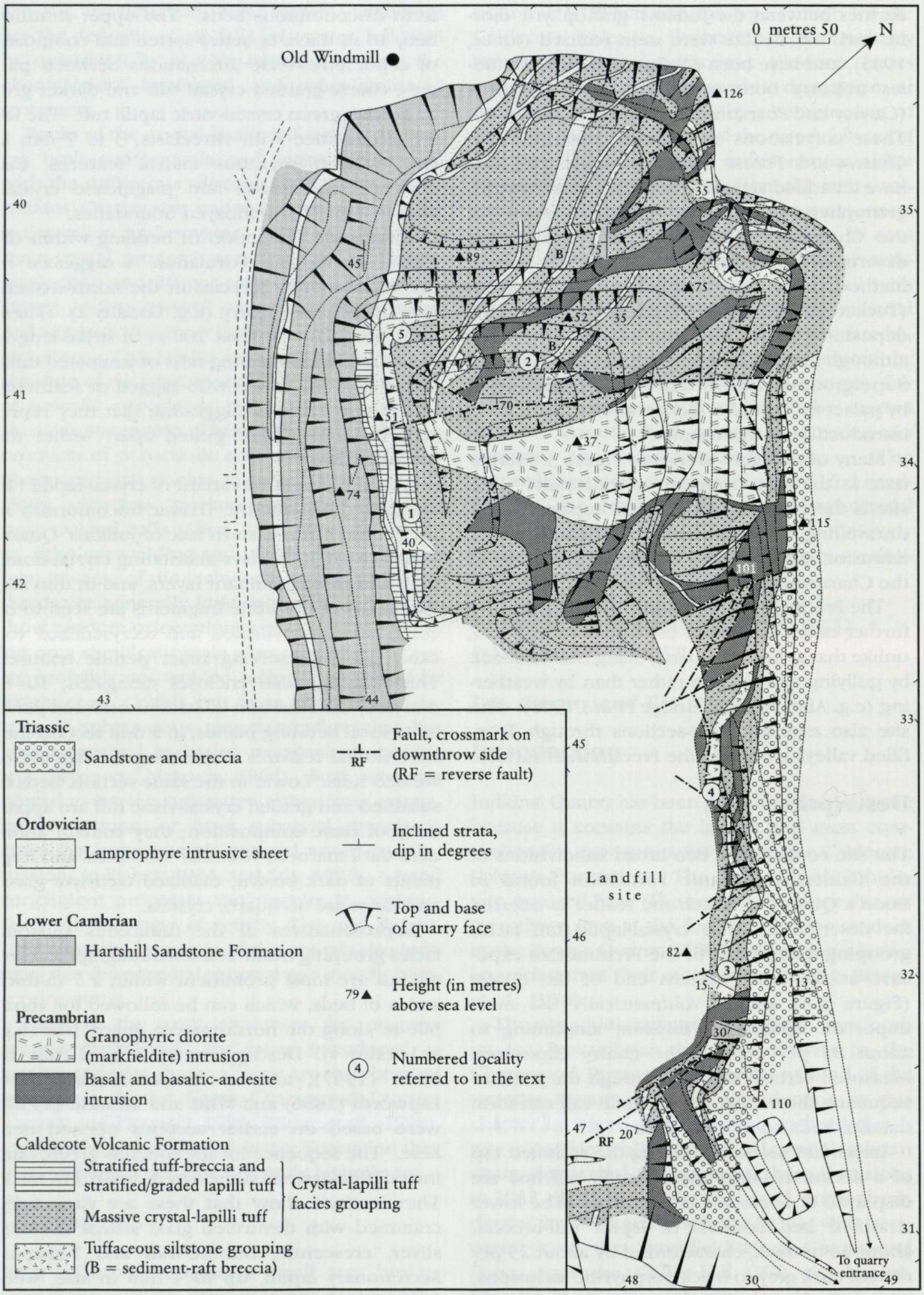

Figure 3.4 Geological map of Judkins' Quarry (from Bridge *et al.*, 1998). The upper north-west levels of the quarry, below the 'Old Windmill', are recommended for conservation in the GCR.

Figure 3.5 Quarry faces in Judkins' Quarry as at 1990, looking north-west. The west-sloping Precambrian–Cambrian unconformity is arrowed, with the Caldecote Volcanic Formation exposed on the right of it. (Photo: A14979, reproduced by kind permission of the Director, British Geological Survey, © NERC.)

Judkins' Quarry, as illustrated in Carney and Pharaoh (1993).

Basic intrusions occupy an estimated 15 per cent of the total Precambrian outcrop in Judkins' Quarry (Figure 3.4). They consist of fine-grained, porphyritic to sparsely-phyric basaltic-andesite and microdiorite sheets that invade many levels of the quarry and form bodies of variable thickness (2–50 m). They have mainly northerly or NNE orientations, which coincide closely with many of the faults truncated at the base-Cambrian unconformity. These intrusions, formerly known as the 'Blue Hole Intrusive Series' (Allen, 1957), are of similar field appearance and geochemistry (Carney and Pharaoh, 1993; Bridge *et al.*, 1998) to the North Charnwood Diorites of Charnwood Forest (Worssam and Old, 1988). Their Precambrian age is demonstrated, uniquely in the Midlands region, at the nearby Boon's Quarry GCR site.

The granophyric diorite body has a north-easterly trend, its margins in part fault-controlled, and it cuts across the mainly north-trending basic intrusions. It was this intrusion that yielded the 603 Ma radiometric age date discussed above. In appearance and geochemistry (Bridge *et al.*, 1998) it is identical to the South Charnwood Diorites of Charnwood Forest. Like the latter (see Cliffe Hill GCR site, Chapter 2), the diorite becomes finer grained towards its contact with the Caldecote Volcanic Formation, developing a dark grey, fine-grained porphyritic facies in which plagioclase euhedra (about 55 per cent) are accompanied by colourless clinopyroxene (20 per cent). Xenoliths form dark grey, fine-grained, angular inclusions in granophyric diorite from the north-western part of the intrusion (Locality 5). Although in hand-specimen they resemble certain of the basalt or basaltic-andesite intrusive rocks, their mineralogy is more appropriate to hornblende microdiorite (Bridge *et al.*, 1998). A zone of darkened country rocks extending over several metres from the intrusive contact is attributed to thermal metamorphism by the diorite.

Near Locality 5, the upper surface of the granophyric diorite is sculpted into gullies infilled by pebbly and conglomeratic sandstone of the Lower Cambrian Hartshill Sandstone Formation, occurring on the next-highest quarry level.

Interpretation

The extensive sections in Judkins' Quarry expose a more complete record of variation within the Caldecote Volcanic Formation than seen in the Boon's Quarry GCR site, but generally support the interpretations already discussed. The role of contemporary pyroclastic activity in supplying fine-grade ash to the depositional basin is emphasized by the occurrence of vitric tuff beds up to 2 m thick, and by the observation of juvenile pyroclastic material (glass shards) admixed within the crystal-lapilli tuffs.

The stratified and graded tuff cappings to certain crystal-lapilli tuff beds are particularly reminiscent of subaqueous pyroclastic flows, as are the distinctive cracked and brecciated crystals (Fisher, 1984). Rapid emplacement of the flows caused instability and flowage within water-saturated, mechanically weak layers represented by the fine-grained sediments, resulting in contorted bedding and in places giving rise to sediment-raft breccias. Evidence for subaerial or phreatomagmatic eruptions, producing pyroclastic surges, is nevertheless provided by the single occurrence of accretionary lapilli and it may be speculated that this activity was linked also to the generation of subaqueous pyroclastic flows. According to Heinrichs (1984), accretionary lapilli can assume a protective outer coating and then be deposited subaqueously without disintegrating. Juvenile quartz, commonly with magmatically embayed boundaries, in association with plagioclase, indicates that the crystal-lapilli tuffs were the products of dacitic magmas. However, relatively thin intercalations of crystal-vitric tuffs that are quartz-poor also suggest contemporary basic or intermediate magma compositions.

Later in the volcanic arc's evolution, magmas became more basic and were introduced as basaltic-andesite (microdiorite) sheets. The younger stock of granophyric diorite, geochemically correlated with the South Charnwood Diorites, represents a high-K calc-alkaline magma emplaced in an arc of increased maturity subsequent to further subduction-enrichment of the mantle source region (Pharaoh *et al.*, 1987b). Most intrusions were preferentially located either along or parallel to faults, demonstrating an important structural control on igneous activity; northerly faulting accompanied the first set of intrusions, but by the time the granophyric diorite was emplaced, the stress regime had shifted and north-easterly faults were formed. Cessation of all magmatic activity, although not necessarily of tectonism, can be dated at, or soon after, 603 ± 2 Ma, the age of the granophyric diorite stock (Tucker and Pharaoh, 1991).

The unconformity with overlying Lower Cambrian marine sandstones is marked by a conglomerate resting on a gullied surface, which has been interpreted as a wave-cut platform (Allen, 1968b; Bridge *et al.*, 1998).

Conclusions

Judkins' Quarry contains the most extensive development of the Caldecote Volcanic Formation seen in the Nuneaton Inlier. It preserves complete cycles of sedimentation, a typical example commencing in dacitic crystal-lapilli tuff that remains massive over thicknesses of up to 50 m before passing up to a relatively thinner, stratified and graded upper part. This kind of variation has its parallel in young volcanic arcs elsewhere in the world and is attributed to the action of subaqueous pyroclastic flows carrying crystal-rich material derived from highly explosive eruptions. The flowage emplacement of these beds is underlined by phenomena indicating mass-instability of the sedimentary pile, such as the horizons of sediment-raft breccia and other soft sediment deformation structures occurring in association with the crystal-lapilli tuffs. The intervening finer-grained beds of tuffaceous siltstone contain accretionary lapilli and these, albeit rare in occurrence, testify to subaerial, or shallow water, pyroclastic activity in the volcanic source region(s). Explosive volcanic activity is typical of quartz phenocryst-rich, dacitic magmas, but the occurrence of quartz-poor tuffs also indicates the coexistence of andesitic or basaltic magmas within this arc system. The quarry exposures demonstrate a full sequence of Precambrian intrusion, post-dating the volcanism. Initially, basaltic to andesitic intrusions, chemically identical to the North Charnwood Diorites of Charnwood Forest, were intruded along northerly-trending faults. They were then cross-cut by north-easterly-trending faults, which in part controlled the margins of a granophyric diorite stock. The radiometric age of 603 Ma for this intrusion therefore constrains a time at which major changes in magmatism and tectonic style were occurring within the

Charnian volcanic arc during the lead-up to its cessation. The fault-bounded Precambrian landmass was subsequently eroded, producing a locally irregular topography at the base of the overlying Lower Cambrian Hartshill Sandstone Formation.