**Natural Environment Research Council**

**British Geological Survey**

**Onshore Geology Series**

**TECHNICAL REPORT WA/97/46**

# Geology of the West Leake area

1:10 000 sheet **SK 52 NW**
Part of 1:50 000 sheet 141 (Loughborough)
and 142 (Melton Mowbray)

**J N CARNEY and A H COOPER**

*Geographical index*
UK, West Leake, East Leake, Ratcliffe on Soar,
Sutton Bonington, North-West Leicestershire

*Subject index*
Geology, Dinantian, Namurian, Sherwood Sandstone,
Mercia Mudstone, Cropwell Bishop Formation,
Tutbury Gypsum, Newark Gypsum,
Scunthrope Mudstone, Quaternary Drift

*Bibliographical reference*
Carney, J N and Cooper, A H.
Geology of the West Leake area (SK 42 NW).
*British Geological Survey Technical*
*Report WA/97/40*

 **Keyworth, Nottingham, British Geological Survey 1997**

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**CONTENTS**

**FIGURES**



**TABLES**

# 1. INTRODUCTION

This report describes the geology of 1:10 000 sheet SK 52 NW (West Leake). The map sheet (hereafter referred to as the 'area') falls in the 1:50 000 Geological sheets 141 (Loughborough) and 142 (Melton Mowbray); it was first geologically surveyed at the one-inch to one-mile scale by E Hull between 1850 and 1860, and published as part of the Old Series One-Inch Geological Sheet 71 SE. The district was re-surveyed on the six-inch scale by C Fox-Strangways in 1892-1895 (Loughborough Sheet) and R L Sherlock in 1906 (Melton Mowbray Sheet) and published on the 1:10 560 County Series Sheets for Leicestershire (L 10 NE), Derbyshire (DY 56 SE) and Nottinghamshire (N 46 SE, 50 NW, 50 SW and 49 SE): detailed sheet compilations are given on the accompanying 1:10 000 map. The New Series One-Inch Geological sheets for Loughborough (141) and Melton Mowbray (142) were published in 1904 and 1909 respectively; accompanying memoirs were also produced (Fox-Strangways, 1905; Lamplugh et al., 1909). After further minor amendments, both sheets were reprinted at the 1:50 000 scale and re-issued in 1976.

Sheet SK 52 NW was resurveyed at 1:10 000-scale by A H Cooper and J N Carney in 1996. This later mapping constitutes part of the Loughborough Geological Mapping Project, under the direction of T J Charsley (Regional Geologist).

The map sheet lies within Nottinghamshire (Rushcliffe) administrative district. It covers a dominantly rural area underlain mainly by Mercia Mudstone, which gives rise to a low-lying and gently undulating terrain. The West Leake Hills are the dominant topographic feature of the area since they are capped by relatively more resistant Jurassic strata: they form a narrow, flat-topped and steep-sided ridge which rises to a maximum elevation of 97 m above OD where overlooking Rushcliffe Golf Course [5405 2835]. To the west the land falls away to the alluvial flats of the River Soar floodplain, at about 33 m above OD, while to the north-east lies flat ground at the same elevation representing the western margin of a depression, the site of a former lake, known as Gotham Moor. The rural land is fully utilised, mainly for arable cultivation supplemented by livestock rearing. There is very little current industrial development, apart from the power station at Ratcliffe on Soar with its desulphurisation plant. Formerly, however, underground gypsum mining was extensive beneath the West Leake Hills, from East Leake north-westwards to beyond Ratcliffe on Soar: various depots, offices, and a large plasterboard-manufacturing complex located just to the east of the area, are the derivatives of that industry.

Corresponding reports covering contiguous 1:10 000 sheets are:

| | | |
|---|---|---|
| SK 53 SW | (Attenborough) | Howard, A S (1989) |
| SK 42 NE | (Kegworth) | Brandon, A and Carney, J N (1997) |
| SK 52 SW | (Normanton on Soar) | Brandon, A (1994) |

An index to the adjacent 1:10 000 geological map sheets is given in Figure 1.

This report should be read in conjunction with the 1:10 000 scale geological sheet SK 52 NW. This shows the outcrop of solid geological formations and superficial deposits which are mostly unexposed, being hidden beneath soil or man-made deposits. Their outcrop limits, represented by geological boundary lines, are mostly inferred from field observations of landforms and soil type, or are extrapolated from adjoining areas, or from borehole records and underground mine plans. The map is therefore the interpretation of the surveyors, based on information to hand at the time of the survey, and all geological boundaries carry an element of uncertainty. Boundaries of solid formations which (in the opinion of the surveyors) can be located to an accuracy of 10 m or less on the ground, are shown as unbroken lines on the map; all other less-certain boundary lines are shown broken.

Copies of the 1:10 000 map can be purchased from BGS, Keyworth. It should be noted that copyright restrictions apply to the use of this map, or parts thereof, and to the direct copying of the illustrative and text material of this report. This report constitutes an internal publication of the BGS and any information extracted from it should be acknowledged by a bibliographical reference (see inside front cover).

Throughout this report, National Grid references are given in square brackets and all lie within 100 km grid square SK. The borehole numbers given are those of the BGS archives where they are prefixed by the number of the 1:10 000 map sheet.

| | | |
|---|---|---|
| SK 43 SE | SK 53 SW | SK 53 SE |
| SK 42 NE | SK 52 NW | SK 52 NE |
| SK 42 SE | SK 52 SW | SK 52 SE |

**Figure 1.** Location of the area with respect to adjacent 1:10 000 mapped sheets

## 2. GENERAL ACCOUNT

A stratigraphical summary of the area is given in Table 1. The oldest rocks, proved only in the Ratcliffe on Soar Borehole, comprise Lower Carboniferous (Dinantian) turbidite mudstones, siltstones and limestones of the *Long Eaton Group* with, at the top, a thick package of turbidite limestones correlated with the *Lockington Limestone Formation.* These beds represent the products of distal sediment gravity flows introduced to a developing intra-Dinantian rifted basin known as the Widmerpool half-graben (e.g. Ebdon et al., 1990); the south-western margin of this basin is the Normanton Hills Fault, which crosses the south-western part of the area. The final basinal sequence, of latest Dinantian, Brigantian age, constitutes the *Widmerpool Formation* of turbidite mudstones and limestones with developments of turbidite siltstones and sandstones. Tuff beds of the *Ratcliffe Volcanic Member* indicate distant volcanic activity of probable late Brigantian, Zone $P_{1d}$ age. The overlying Upper Carboniferous (Namurian) succession in the Ratcliffe Borehole is correlated with Pendleian-age sequences in the Duffield Borehole, and is referred to the *Edale Shale Group.* It comprises calcareous mudstones which coarsen upwards into turbiditic siltstones and sandstones just below the Trias unconformity. The Edale Shales were deposited after fault-controlled subsidence had largely ceased, and thus represent an infill formed during the thermal subsidence phase of the Widmerpool half-graben (Ebdon et al., 1990)

End-Carboniferous (Variscan) earth movements caused reversal of the Normanton Hills Fault, as part of a general phase of compression, uplift and erosion of the Carboniferous basinal and post-basinal sequences.

The earliest Triassic strata, encountered in the Ratcliffe Borehole, comprise a thin development of the *Moira Formation.* This unit probably includes breccias with volcanic (?Charnian) clasts, and represents deposition in hollows or shallow valleys on a land surface of eroded Carboniferous strata. The succeeding beds in this borehole are of the largely Anisian (early Middle Triassic)-age *Bromsgrove Sandstone Formation,* the sole representatives of the *Sherwood Sandstone Group* in the area. There are no lithological details, but it is probable that they mainly consist of fine- to medium-grained sandstones which may be the deposits of braided river systems with wide, sandy flood plains.

The succeeding beds of the *Mercia Mudstone Group* comprise, at the base, micaceous mudstones, siltstones and sandstones of the *Sneinton Formation.* These strata, formerly known as 'Waterstones', represent a later stage of aggradation in the East Midlands region during which predominantly fine-grade detritus was carried by mature rivers characterised by wide floodplains and/or areas of channel abandonment that supported ephemeral bodies of standing water. In the overlying *Radcliffe Formation,* lacustrine deposition predominated resulting in a well-laminated mudstone-siltstone sequence. The *Gunthorpe Formation,* of Ladinian age, is the oldest Triassic unit to crop out, south-west of the Normanton Hills Fault. It chiefly consists of red mudstones and silty mudstones representing accumulations of fine-grained terrigenous sediment transported by wind or water, and deposited partly subaerially and partly in shallow, low-energy subaqueous environments (Jeans, 1978). Short-lived episodes of fluvial, sheetflood, arenaceous deposition gave rise to several intercalated beds of siltstone and fine-grained sandstone. Similar environments prevailed during deposition of the Carnian-age (Upper Triassic) *Edwalton Formation;* however, fluvial activity was accentuated, producing thicker and more numerous sandstone and siltstone beds. The latter are exemplified by the *Cotgrave Sandstone Member* and the *Hollygate Sandstone Member*, respectively defining the lower and upper parts of the unit. The Hollygate Sandstone is correlated with the Arden Sandstone of the West Midlands, which according to Old et al. (1991) represents a major environmental change to deposition within distributary channels and interdistributary channels in a deltaic or estuarine setting (Warrington and Ivimey-Cook, 1992). The overlying *Cropwell Bishop Formation* represents a reversion in Norian times to conditions prevailing during Gunthorpe Formation deposition, with thick beds of sulphate evaporites, exemplified by the *Tutbury Gypsum* and *Newark Gypsum*, representing concentrations from interstitial brines or shallow hypersaline water bodies in arid environments (Warrington and Ivimey-Cook, 1992). The brine source regime for these deposits was continental according to Taylor (1983). The youngest unit of the Mercia Mudstone, comprising the green mudstones of the *Blue Anchor Formation*, of Norian to Rhaetian age, may have been deposited from waters with a mixed marine-continental origin according to Taylor (1983); supratidal sabkha environments bordering a hypersaline marine water body are envisaged for this unit by Warrington and Ivimey-Cook (1992).

The Rhaetian-age *Penarth Group* commences with mudstone deposition, in the *Westbury Formation*, that followed a marine transgression across the area (e.g. Warrington and Ivimey-Cook, 1992). The overlying and rather more calcareous *Lilstock Formation*, represented only by the *Cotham Member*, may have been deposited within shallow-water lagoonal environments (Warrington and Ivimey-Cook, 1992).

The *Lias Group* is represented by the *Scunthorpe Mudstone Formation* of which only the basal unit, the *Barnstone Member,* is present in the area. The mudstones in the lower part of the member contain the Triassic/Jurassic boundary. Above this is a Hettangian-age sequence, of mudstones alternating with locally shell-rich limestones, representing the deposits of warm tropical seas.

Post-Triassic tectonism resulted in gentle tilting, faulting and localised monoclinal flexuring in the area. The displacement of c. 150 m along the principal structure, the Normanton Hills (Hoton) Fault, represents at least its third rejuvenation since formation of the Widmerpool half-graben in lowermost Carboniferous times. Other faults with northerly trends probably reflect the influence of rejuvenated deep basement structures.

Any strata deposited between the Lower Jurassic and Quaternary periods were removed by erosion in Mesozoic to Cenozoic times.

The earliest Quaternary deposits comprise till derived from ice sheets which inundated the area. The age of this glacial advance was previously placed within the 'Wolstonian' (Saalian of Europe) Stage of the Upper Pleistocene (e.g. Rice, 1968), but the weight of new evidence from the English Midlands now suggests that it was older, belonging to the Middle Pleistocene (Anglian) Stage during which was deposited the glacial drift of East Anglia and Warwickshire (Sumbler, 1983). The till mainly seen in the present area is correlated with the *Thrussington Till*, its red matrix and clasts of mainly Triassic and Carboniferous derivation indicating deposition from an ice sheet advancing from the north-west, while localised melt-waters provided the more extensive outcrops of flinty sands and gravels representing *Glaciofluvial Deposits.*

The present topography of the area is a legacy of erosion and deposition during these phases of ice advance and decay and the associated incision initiated by meltwaters. The floodplain sediments of the River Soar and its tributaries were modified by successive stages of climatically controlled aggradation, vertical incision and lateral incision. They are now preserved as flights of terraces underlain by fluvial sands and gravels. In the Soar valley these are referred to the *Birstall, Wanlip and Syston terraces*. The coarse-grained sands and gravels accumulated in cold stadials when valley flanks were being greatly modified by mobile periglacial slope deposits. Early Flandrian *Older Alluvium* forms a low terrace above the modern Soar floodplain.

The youngest unit in the area consists of modern riverine *Alluvium.* Gotham Moor is floored by organic and shell-rich *Lacustrine Deposits* which were probably accumulated within a shallow depression during a time in the Flandrian period when surrounding water levels were high. Slope deposits referred to as *Head* are of widespread distribution: they mainly comprise clayey silt and sand mobilised downslope by rain wash and/or processes of gelifluction and solifluction. On the steep southern flanks of the West Leake Hills, slope instability has given rise to *Landslips*.

| AGE | STRATIGRAPHIC UNIT | THICKNESS (m) |
|---|---|---|
| QUATERNARY | DRIFT: | |
| | Landslip | |
| | Head | ? |
| | Alluvium | up to ~3 |
| | Lacustrine Deposits | 1-2 |
| | River Terrace Deposits: | |
| | Older Alluvium | up to 3.7 |
| | Syston Sand and Gravel | c. 2 |
| | Wanlip Sand and Gravel | c. 2 |
| | Birstall Sand and Gravel | c. 3 |
| | Glaciofluvial Deposits | up to ?10 |
| | Thrussington Till | up to c. 10 |
| JURASSIC | | |
| | LIAS GROUP: | |
| | Scunthorpe Mudstone Formation: | |
| | Barnstone Member | 9+ |
| TRIASSIC | | |
| | PENARTH GROUP: | |
| | Lilstock Formation: | |
| | Cotham Member | 4 |
| | Westbury Formation | 5-8 |
| | MERCIA MUDSTONE GROUP: | |
| | Blue Anchor Formation | 7-10 |
| | Cropwell Bishop Formation | 66 |
| | Edwalton Formation: | 50 |
| | Hollygate Sandstone Member | ~8 |
| | Cotgrave Sandstone Member | 2-4 |
| | Gunthorpe Formation | 74 |
| | Radcliffe Formation | 10 |
| | Sneinton Formation | 30 |
| | SHERWOOD SANDSTONE GROUP: | |
| | Bromsgrove Sandstone Formation | 48 |
| | Moira Formation | 5 |
| UPPER CARBONIFEROUS (SILESIAN) | EDALE SHALE GROUP | 166+ |
| LOWER CARBONIFEROUS (DINANTIAN) | Widmerpool Formation: | 741 |
| | Ratcliffe Volcanic Member | 124 |
| | LONG EATON GROUP: | 675+ |
| | Lockington Limestone Formation | 143 |

**Table 1.** Sequence of geological units in the West Leake area (NB some of these subdivisions may be revised at a later date, and may thus appear with different names on subsequent published 1:10 000 or 1:50 000 maps)

# 3. LOWER CARBONIFEROUS (DINANTIAN)

## 3.1. Carboniferous Limestone (Visean)

A partial Carboniferous Limestone sequence was proved in the BP plc Ratcliffe on Soar hydrocarbon exploration borehole (SK 52 NW/72)[1], between 416 m and the base of the borehole at 1832 m depth (Figure 2). The strata belong to the basinal, or off-shelf facies of the Carboniferous Limestone, and were deposited, probably in part as distal sediment gravity flows, during the waning stages of subsidence within the Widmerpool half-graben (e.g. Ebdon et al., 1990).

The completion log for the Ratcliffe Borehole gives in broad outline the chronostratigraphy of these strata which was, however, largely based on micropalaeontological determinations of cuttings samples carried out soon after drilling, in the late 1980's. That particular interpretation is here revised substantially. For those strata below about 700 m depth, important changes have been made in the light of a re-assessment of the micropalaeontology of samples from the Long Eaton No.1 Borehole, located 9 km to the north-west; this is explained more fully in Riley (1997). The Long Eaton data can with some confidence be applied to the Ratcliffe Borehole since for the interval in question, the gamma and sonic log signatures are identical. For the strata above 700 m depth, not represented at Long Eaton, a further revision of the chronology, and a classification of the units present, is based on a comparison between the gamma ray logs for Ratcliffe on Soar and the fully-cored BGS Duffield Borehole (Aitkenhead, 1977), as shown in Figure 2.

In an early version of the relevant BGS report (Brandon, 1996), the Long Eaton No.1 sequence was informally named for equivalent off-shelf units in the Craven Basin of Lancashire, which are of a similar age and structural style to the Widmerpool half-graben. This scheme was subsequently revised (see nomenclature on GVS for Sheet SK 43 SE), with local names established. The present report uses this later scheme for the lower part of the Ratcliffe borehole sequence, but names certain of the younger units on the basis of their correlations with similar formations in adjacent districts.

### 3.1.1. Long Eaton Group

The Long Eaton Group comprises a 675 m minimum thickness of strata, between 1157 m and the termination of the Ratcliffe Borehole at 1832 m depth. The wireline log signatures enable it to be correlated with the upper part of the 1867 m minimum thickness of beds in the Long Eaton No.1 Borehole, which was informally referred to as the 'Worston Shale Group Equivalent' by Brandon (1996). The single subdivision comprises the Lockington Limestone Formation, located at the top of the sequence.

In the Long Eaton No.1 Borehole the age of the Long Eaton Group ranges down from the Asbian/Brigantian boundary to the early Chadian and late Tournasian; however, this sequence

[1]For details of selected boreholes see Section 11

also appears to contain a depositional hiatus since there is no evidence for late Chadian or Arundian strata being present (Riley, 1997). Wireline log correlations suggest that the equivalent strata represented in the Ratcliffe on Soar Borehole are largely of Asbian age (although this is somewhat equivocal, as noted by Riley, for the relevant section in the Long Eaton No.1 Borehole), with the Asbian/Brigantian boundary located in the middle to upper part of the Lockington Limestone Formation.

On the borehole log, brief descriptions of sidewall core samples suggest that the undivided part of the Long Eaton Group consists mainly of dark grey or brown, silty to very silty calcareous mudstones with finely-disseminated pyrite. The mudstones contain sporadic and thin beds of white, beige or brown micritic limestone, which is commonly pyritic and sandy; they may correspond to the graded beds of siltstone, calcisiltite, packstone and grainstone seen in the Long Eaton No.1 Borehole, which are interpreted as Bouma A to D-phase turbidites (Brandon, 1996).

Lockington Limestone Formation

This unit is named for the 143 m sequence between 1157 and 1300 m depth in the Ratcliffe on Soar Borehole. It is characterised by an irregular gamma-ray profile (Figure 2) which corresponds well with that shown by a similar section in the Long Eaton No.1 Borehole, although it is rather thicker there, at 185 m. Brandon (1996) referred to the latter sequence as the 'Pendleside Limestone Group Equivalent'.

The gamma ray profile of the Ratcliffe on Soar Borehole suggests that the Lockington Limestone Formation comprises four limestone-dominated packages, each between 15 and 35 m thick, separated by 5-15 m thick mudstone-rich sequences. Descriptions of sidewall core samples indicate that the limestones are typically pale brown or beige, micritic lithologies that are argillaceous to very sandy and show all gradations to calcareous sandstone. The mudstones are grey to brown, pyritic, slightly silty and locally carbonaceous. Sidewall core samples from the equivalent beds in the Long Eaton No.1 Borehole suggest a sequence of interbedded turbidite limestones, mudstones and subordinate sandstones (Brandon, 1996).

3.1.2. Widmerpool Formation

The Widmerpool Formation (Institute of Geological Sciences, 1968, p.88; Aitkenhead, 1977; Aitkenhead and Chisholm, 1982, p.12) is identified as the 741 m thickness of strata between 416 and 1157 m depth in the Ratcliffe on Soar Borehole. Variations in wireline log signatures, supported by sample descriptions, enable the Ratcliffe Volcanic Member to be separated out, within the upper part of the formation (Figure 2).

The lower, undivided part of the Widmerpool Formation is correlated with the highest Carboniferous beds intersected below the Trias in the Long Eaton No.1 Borehole (Brandon, 1996). Fauna from that section have yielded a Brigantian age (Riley, 1997), and it is assumed here that the whole of the unit in the Ratcliffe Borehole belongs to the same stage.

Below the Ratcliffe Member, descriptions of cuttings and sidewall core samples given on the borehole log indicate that the beds mainly consist of dark brown to pale brown or greyish brown, calcareous and locally carbonaceous mudstones which are pyritic and silty, and which can grade to argillaceous limestone. Also present are thin beds of white, pale grey or pale brown, micritic limestone which locally grades into calcareous mudstone. A thin bed of greyish brown, fine- to medium-grained calcareous sandstone was noted on the borehole log to occur at 873 m depth. The equivalent beds in the Long Eaton No.1 Borehole were similarly rather variable, and described as forming part of a deep-water turbidite sequence by Brandon (1996).

Above the Ratcliffe Member, 91 m of Widmerpool Formation beds occur between 507 m and the base of the Namurian, estimated to lie at 416 m depth (Section 4.1). In the lower part of this sequence, between 507 m and 468 m depth, cuttings samples indicate mudstones with several white to pale grey limestone beds between 1 m and 5 m thick. The upper part is a 30 m-thick sandstone-rich sequence, between 468 and 438 m depth, which on the basis of its gamma ray signature correlates with the interbedded turbidite mudstones, siltstones and sandstones encountered at the top of the Upper *Posidonia* ($P_2$) Zone in the Duffield Borehole (Figure 2). Cuttings samples described in the Ratcliffe Borehole log indicated a thinly-interbedded sequence of white to pale grey sandstone, with siliceous cement, alternating with beds that included pale brown, argillaceous and micritic limestone.

Above these sandstones, the 22 m-thick sequence up to the inferred base of the Namurian comprises mudstones with several thin (~1 m) limestone beds, the latter becoming more numerous near the base. A limestone cuttings sample was described as dark brown and micritic.

Ratcliffe Volcanic Member

This unit is newly-named here, for the 124 m thick sequence of beds between 507 and 631 m depth in the Ratcliffe on Soar Borehole. On the gamma ray log it is distinguished by the occurrence of 6 prominent left-pointing 'spikes', interpreted on the completion log as tuff beds between 2 and 15 m thick. Cuttings samples described in the borehole log indicate that two of these datums do correspond to 'tuff' lithologies; they are pale bluish grey, pyritous, silty and calcareous, with some alteration to 'kaolinite' noted. Shards were described from the topmost tuff bed. Separating the tuffs are sequences of olive green to brown, silty, slightly carbonaceous and pyritic mudstones. Limestone beds 1 m or less in thickness are interspersed throughout the unit: cuttings samples show that they are brown to beige micritic lithologies.

It is possible that the Ratcliffe Member records distant volcanism prevailing at about the time of the Tissington Volcanic Member in the Ashbourne district. That unit comprises a diverse volcanic assemblage of basaltic character, occurring within a sequence dated by ammonoids at between $P_{1c}$ and early $P_2$ age, probably within the $P_{1d}$ Zone (Chisholm et al., 1988, p.33). The Ratcliffe Member is more precisely correlated, by its gamma ray signature, with a tuffaceous sequence, of $P_2$ age, encountered over a 130 m thickness in the Duffield Borehole (Aitkenhead, 1977, and Figure 2 of this report).

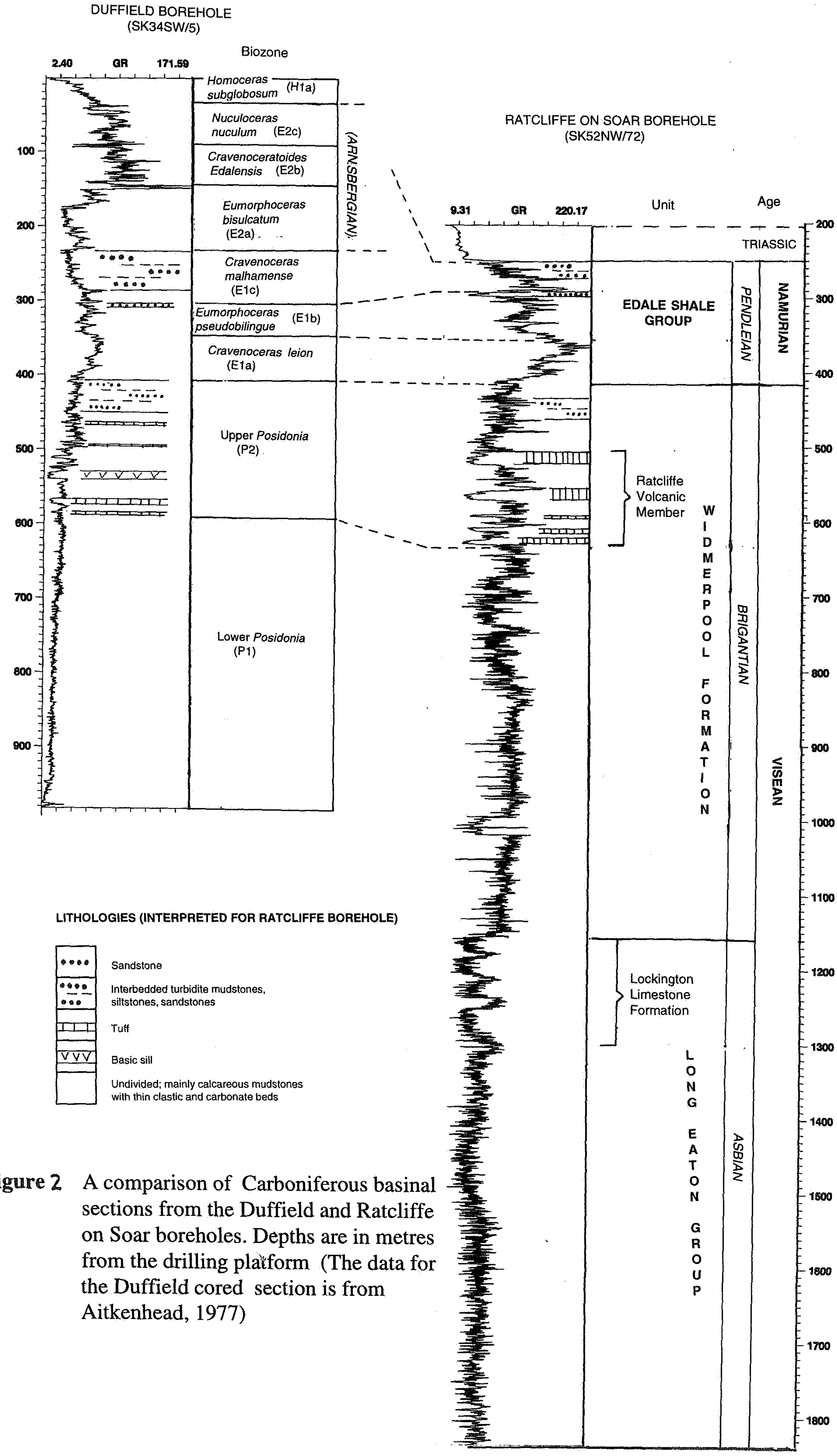


**Figure 2** A comparison of Carboniferous basinal sections from the Duffield and Ratcliffe on Soar boreholes. Depths are in metres from the drilling platform (The data for the Duffield cored section is from Aitkenhead, 1977)

## 4. UPPER CARBONIFEROUS (SILESIAN)

### 4.1. Edale Shale Group (Namurian)

Strata correlated with the Edale Shale Group are 166 m thick in the Ratcliffe on Soar Borehole. They were encountered between the top of the Dinantian (Widmerpool Formation), inferred to lie at 416 m, and the base of the Triassic at 250.3 m depth. Figure 2 shows that this sequence may with some confidence be correlated with that in the Duffield Borehole, for which detailed lithological and gamma ray logs are available for comparison (Aitkenhead, 1977). The basis for this correlation is reinforced by the fact that relative to the margins of the Widmerpool half-graben as portrayed by Ebdon et al. (1990, Fig. 3), the Ratcliffe and Duffield boreholes lie in a similar structural position. The correlations suggest that a substantial revision is needed to the chronostratigraphy presented on the Ratcliffe on Soar Borehole completion log; in particular, the base of the Namurian is now believed to lie at 416 m depth, as opposed to the 385.8 m formerly stated, and the Arnsbergian Stage is not represented.

The base of the Namurian is determined from the gamma ray log which shows (Figure 2) a prominent inflection, marking a change to higher gamma ray values, replicating the gamma ray profile of the Duffield Borehole at the point that was taken to mark the start of the Pendleian, *Cravenoceras leion* Zone ($E_{1a}$ Zone). In the Ratcliffe Borehole this horizon is succeeded by c. 58 m of mudstones, which are dark grey and calcareous according to one sample described in the log.

At c. 358 m depth, a change to lower gamma ray values is correlated with the inflection marking the base of the '*E. pseudobilingue*' ($E1_b$) Zone as identified in the Duffield Borehole, which there occurs about 60 m above the *C. leion* zonal base. On this criterion, the Ratcliffe Borehole completion log must be considerably in error since it places the Pendleian-Arnsbergian boundary about here, at 360.8 m depth.

A further 68 m above the inferred *E. pseudobilingue* zonal base, a change to high gamma ray values, at 290 m depth, is correlated with an identical feature marking the base of a further Pendleian zone, that of *Cravenoceras malhamense* ($E_{1c}$), in the Duffield Borehole. The c. 7 m thick sandstone immediately below, which gives rise to a complementary low gamma ray spike (Figure 2), is described from samples as being pale yellow and fine- to medium-grained, with a calcareous to siliceous cement. It is directly equated with the c. 9 m thick sequence of graded, turbidite sandstones below the *C. malhamense* Zone in the Duffield Borehole (Aitkenhead, 1977). The remaining 40 m of strata, up to the base of the Trias, coarsens up into c. 20 m of interbedded sandstones and mudstones. A sample description suggests that the sandstone is pale brown and fine-grained, with a 'grainstone' texture. The equivalent section in the Duffield Borehole records interbedded, sharp-based graded layers consisting of sandstone and siltstone fining up to mudstone, and is located just below the top of the Pendleian Stage (Aitkenhead, 1977).

## 5. TRIASSIC

The lithostratigraphical subdivision of the Triassic rocks in this report follows the scheme of

Warrington et al. (1980), as modified by Charsley et al. (1990). The four principal divisions comprise a basal Moira Formation overlain by the Sherwood Sandstone Group, Mercia Mudstone Group and Penarth Group.

## 5.1. Moira Formation

The Moira Formation is a variable sequence whose components may include mudstones, sandstones and breccias. Elsewhere it is regarded as an unconformity-bounded unit, representing sequences that infilled hollows on the Carboniferous landsurface, but which were affected by earth movements before being overlain by the Sherwood Sandstone Group (Carney, 1996). The unit was originally called the 'Permian breccias' or 'Permian marls' in the Loughborough district (Fox-Strangways, 1905), and the 'Moira Breccia' in the Coalville district (Worssam and Old, 1988). It has recently been re-named the Moira Formation (Carney, 1996) because in many areas breccias may be absent or subordinate in proportion to the other lithologies.

The age of the Moira Formation is not precisely known, since these beds are generally lacking in dateable fossil remains. In the West Midlands the equivalent strata, called the Barr Beacon Beds and the Hopwas Breccia, were thought to be Permian in age by Smith et al. (1974). Recently, however, a comparative palaeomagnetic study of samples from the Enville Formation, Hopwas Breccia and Kidderminster Sandstone (Sherwood Sandstone Group) of the West Midlands has concluded that the Hopwas Breccia is probably of early Triassic (earliest Scythian) age, and that very little time had elapsed between its deposition and that of the overlying Kidderminster Sandstone (Oral communication, J H Powell, 1996).

In the present area, the Moira Formation is possibly represented in the Ratcliffe on Soar Borehole, between 245 and 250.3 m depth, by a 5 m thick sequence at the base of the Triassic. The borehole log describes a cuttings sample consisting of 'conglomeratic' sandstone with clasts of dark green igneous rock in a reddish brown, argillaceous matrix. By analogy with Moira Formation lithologies elsewhere (Carney, 1996), the igneous clasts are probably in the main derived from the Precambrian rocks of Charnwood Forest. An extension of the Moira Formation a few metres higher in the borehole cannot be entirely discounted, if the sequence with the high gamma ray values in Figure 3 represents an upper, sandstone- and breccia-impoverished facies of the Moira Formation rather than the basal part of the Bromsgrove Sandstone.

## 5.2. Sherwood Sandstone Group

### 5.2.1. Bromsgrove Sandstone Formation

The Bromsgrove Sandstone Formation, of mainly Anisian age (Warrington et al., 1980), typically comprises sequences of fine- to medium-grained sandstones with subordinate interbedded mudstones and siltstones. In the Loughborough district it was formerly called the 'Lower Keuper Sandstone and Marls' (Fox-Strangways, 1905).
In the present area the unit is estimated to be 48.5 m thick. It was encountered only in the Ratcliffe on Soar Borehole, where strata between 196.5 and 245 m depth show predominantly low gamma ray values (Figure 3) indicative of a sandstone-rich sequence with probable mudstone and siltstone intercalations. A single cuttings sample from near the top of the unit was

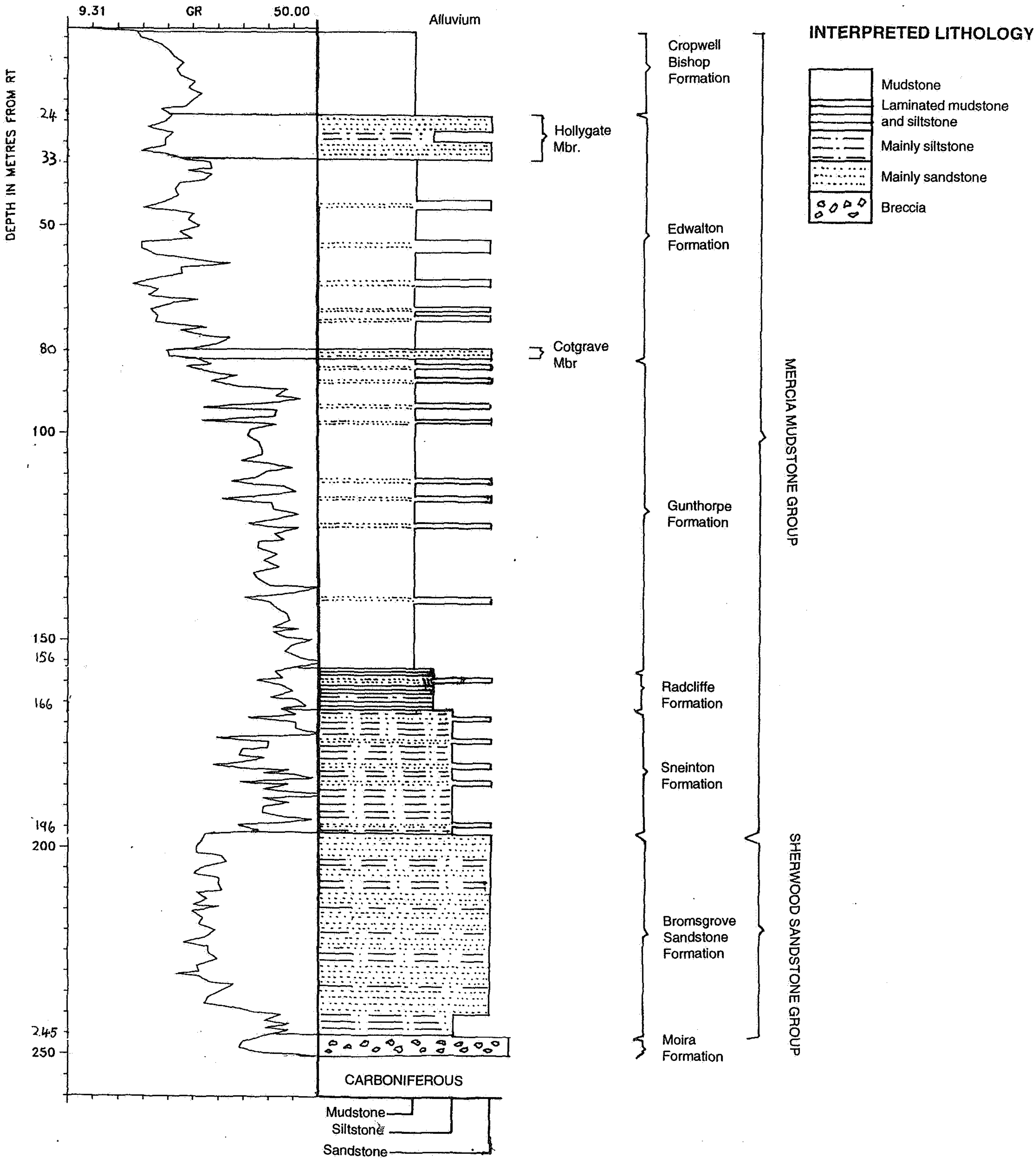


**Figure 3.** Interpretative section in Triassic strata: Ratcliffe on Soar Borehole (SK52NW/72)

described as a white, fine- to medium-grained sandstone which is rather poorly sorted, with sporadic coarse sand-size grains.

The lithology of the cuttings sample suggests its correlation with Bromsgrove Sandstone, rather than with the Nottingham Castle Sandstone Formation which is coarser-grained and has a significant pebble content. In the absence of more comprehensive descriptions, however, any correlation of the Ratcliffe Borehole sequence will be equivocal. The Bromsgrove Sandstone is the only constituent of the Sherwood Sandstone Group in the adjacent area to the west (Brandon and Carney, 1997). However, to the north the basal Triassic sandstones, comprising a 37.9 m thickness in a borehole at Chilwell, include a lower pebbly facies and were correlated with the Nottingham Castle and Lenton formations of the Sherwood Sandstone Group (Howard, 1989). To the south, Bromsgrove Sandstone ranging between 28.7 and 42.8 m thick was proved in boreholes at Hathern and Sutton Bonington brickyard, but these beds were further underlain by conglomeratic sandstones between 18.9 and 25 m thick (Brandon, 1994). The latter sequences were tentatively corrrelated with the Nottingham Castle Sandstone Formation, although they contain probable Charnian clasts which would indicate a significant local detrital input.

### 5.3. Mercia Mudstone Group

The Mercia Mudstone Group is divided (Table 1) into formations and members according to the scheme of Charsley et al. (1990). The whole of the group, amounting to 243 m thickness, is represented in this area.

#### 5.3.1 Sneinton Formation

The Sneinton Formation, of Anisian to Ladinian age, was named by Charsley et al. (1990) for the sequence of interbedded, laminated and micaceous mudstones, siltstones and sandstones, basal to the Mercia Mudstone Group, which formerly was referred to as the 'Waterstones'.

In the present area the formation, about 30 m thick, was encountered only in the Ratcliffe on Soar Borehole. It was identified on the basis of its characteristically serrated gamma ray signature on the wireline log, between 166 and 196.5 m depth (Figure 3), which compares with the gamma ray profile of the same formation in the well-documented and fully-cored Cropwell Bridge Borehole (Howard et al., in prep.). A single cuttings sample from the relevant part of the Ratcliffe Borehole section was described in the completion log as consisting of brown to pale brown, fine- to medium-grained sandstone with a calcareous cement.

#### 5.3.2. Radcliffe Formation

The Radcliffe Formation was defined by Elliott (1961), who described it as a sequence of laminated and colour-variegated mudstones and siltstones with sporadic beds of fine-grained sandstone and cemented siltstone. It is considered to be mainly Ladinian in age (Warrington et al., 1980).

The formation is tentatively identified in the Ratcliffe on Soar Borehole as a c. 10 m thick sequence between 156 and 166 m depth (Figure 3). No other lithological details exist.

### 5.3.3. Gunthorpe Formation

The Gunthorpe Formation, of Ladinian age, was distinguished by Charsley at al. (1990) to include the Mercia Mudstone units formerly called the Carlton and Harlequin formations by Elliott (1961). This re-classification took into account the fact that in many areas the resistant bed of the 'Plains Skerry', separating the Carlton and Harlequin formations in Elliott's scheme, could not easily be distinguished from other beds of similar lithology occurring within the sequence.

In the present area a full 74 m thickness of the Gunthorpe Formation is inferred from the gamma ray signature of the beds encountered in the Ratcliffe on Soar Borehole, between 156 m and the gamma ray 'spike' identified as the Cotgrave Sandstone at about 81 m depth (Figure 3). The unit crops out only in the south-west of the area, on the upthrown side of the Normanton Hills Fault.

The formation typically consists of interbedded red-brown and grey-green mudstone or silty mudstone which can either be massive (blocky) or poorly laminated. It forms a sequence containing many thin (~1 m) composite beds of competent green, grey and buff dolomitic siltstone and/or fine-grained sandstone.

*Details*

The completion log of the Ratcliffe on Soar Borehole provides only sparse lithological information, from cuttings samples of the formation at about 105 m depth. They indicate the presence of reddish brown to greenish grey, blocky to 'sub fissile', firm to moderately hard mudstone. The samples were very silty, slightly micaceous, and showed gradations to calcareous or dolomitic siltstone.

The Gunthorpe Formation outcrop south-west of the Normanton Hills Fault is largely covered by Quaternary deposits. Where at the surface it is generally not exposed, being easily weathered, but its presence is commonly revealed in ploughed fields as debris (brash) composed of red mudstone and silty mudstone. It is noted that the outcropping part of the formation is likely to be deeply weathered (see also, Section 5.3.5.).

To the south of St. Anne's Manor, a resistant bed ('skerry') within the formation gives rise to a prominent ledge-like feature along the top of the slope [5092 2512]. Debris from a recent utilities trench shows that this bed, about 1-2 m thick, consists of indurated and calcareous, pink to green micaceous siltstone.

The stratigraphical position of several other sandstone beds is indicated by certain of the more prominent left-pointing serrations on the Ratcliffe Borehole gamma ray log (Figure 3).

### 5.3.4. Edwalton Formation

The Edwalton Formation was named by Elliott (1961), and has been tentatively assigned a Ladinian to Carnian (Upper Triassic) age by Warrington et al. (1980). It mainly consists of reddish brown and greyish green siltstone and mudstone, which is typically blocky or poorly laminated. The base of the unit is also the base of the Cotgrave Sandstone Member (formerly the

Cotgrave Skerry), and its top is the top of the Hollygate Sandstone Member, these comprising the only two subdivisions of the formation.

The formation does not crop out in this area, but thicknesses of between 50 and 58 m can be inferred from borehole data. The gamma ray log for the Ratcliffe on Soar Borehole, for example, suggests that the Cotgrave Sandstone may correspond to a low-gamma ray spike with a base at about 81m depth, and the Hollygate Sandstone to a broader, more poorly-defined series of low-gamma ray spikes whose top lies at about 23 m depth (Figure 3). On the other hand, confidential logs for deep cored boreholes at Ratcliffe on Soar Power Station are better-described and they indicate a maximum thickness of 50 m. The latter is taken as the most precise thickness estimate, with the proviso that it may locally be exceeded, as in the Ratcliffe on Soar Borehole.

*Details:*

In the Ratcliffe on Soar Borehole, a description in the log of cuttings samples taken from near the top of the Edwalton Formation, at about 40 m depth, indicated reddish brown, firm, blocky to slightly 'fissile' mudstone which was calcareous and very silty, grading to siltstone. The presence of an appreciable detrital content, which may include sandstone beds, is also indicated by the distinctively serrated gamma ray profile of the formation in that borehole (Figure 3). Confidential borehole logs for the Ratcliffe Power Station show four sandstone beds within the Edwalton Formation, and further indicate that the enclosing red-brown mudstones are gypsiferous, and commonly of a very silty to sandy composition.

Cotgrave Sandstone Member

This basal subdivision of the Edwalton Formation corresponds to the 'Cotgrave Skerry' of Elliott (1961). In the Ratcliffe Borehole log, the gamma ray spike correlated with this unit, at 79-81 m depth, suggests it is about 2 m thick. A description of a cuttings sample taken from about this datum indicated a grey-green, hard, fine- to medium-grained argillaceous sandstone with a dolomitic cement; fibrous gypsum was present locally.

Borehole logs for the Ratcliffe on Soar Power Station site (held in confidence at NGRC; see Section 11) indicate an unusual thickness of sandstone, 4.25 m, forming a bed whose base lies about 42 m below the Hollygate Sandstone - in the correct stratigraphical position for correlation as the Cotgrave Member. The sandstone is greyish green, fine-grained and argillaceous, with local reddish brown, silty partings. A further sandstone, 1.5 m thick, lies 1.45 m above it.

Hollygate Sandstone Member

This member corresponds to the 'Hollygate Skerry' of Elliott (1961), and is the stratigraphically highest subdivision of the Edwalton Formation. Warrington et al. (1980) referred to the unit as a member but did not precisely define it: they tentatively assigned it a Carnian age. The thickness, lithology and age of this member invite correlation with the Arden Sandstone of the West Midlands (e.g. Old et al., 1991, p.32), as discussed further in Section 2.

*Details:*

In the Ratcliffe Borehole the section occupied by the member is thought to correlate with the rather diffuse low-gamma ray spike between about 24 and 33 m depth (Figure 3).

Beneath the Ratcliffe Power Station site, the unit is identified on confidential borehole logs over a maximum thickness of about 8 m. It forms a composite sequence, commonly comprising 5 beds of pale grey, fine-grained, gypsiferous sandstone with the thickest bed (up to 2 m) generally occurring at the base and the higher beds averaging between 0.4 and 1.7 m thick. Separating individual beds are layers of red-brown, gypsiferous mudstone. Appreciable local variation is indicated within the small area of the Power Station site, with some provings of the Hollygate Member showing four thinner beds of fine- to medium-grained sandstone alternating with mudstone within a c. 3 m thick sequence.

5.3.5. Cropwell Bishop Formation

Recent BGS mapping in the Nottingham district has indicated that, in practice, there is only a single mappable formation between the Edwalton Formation and the base of the Blue Anchor Formation, to which the name Cropwell Bishop Formation was assigned (Charsley et al., 1990). A probable Norian age is advocated for equivalent beds elsewhere (Oral communication, G W Warrington, 1996).

In the present area the formation either crops out or subcrops extensively at shallow depths beneath Quaternary deposits to the north-east of the Normanton Hills Fault. There are no complete provings that give the precise thickness of the formation, but an assessment of approximately 50 confidential intermediate-depth (c. 30-100 m) boreholes shows that the Tutbury Gypsum forms a useful stratigraphical marker bed, with its base generally about 28 m above the top of the Hollygate Sandstone, and 38 m below the Blue Anchor Formation. These stratigraphic considerations suggest that the formation's total thickness is about 66 m. This is considerably greater than the 48 m estimated for the formation in the adjacent sheet to the north (Howard, 1989), and across the Nottingham district in general (Charsley et al., 1990).

The lithologies of the Cropwell Bishop Formation mainly consist of reddish brown gypsiferous mudstones and siltstones which are mostly blocky, but also feature lamination at certain levels. Beds of indurated greyish green siltstone and fine-grained sandstone occur at other levels. Certain of the more recent borehole logs indicate that in keeping with the other Mercia Mudstone formations the shallowly-outcropping or subcropping parts of the Cropwell Bishop Formation are weathered, down to at least 20 m (in Borehole No. 95), with weathering zones IV to II (Chandler and Davis, 1973) being identified. The degree of heterogeneity imposed by this weathering will be further exacerbated in those parts of the sequence where gypsum dissolution has occurred (Section 9.4), and such zones are commonly also associated with enhanced permeability.

Particularly distinctive to the Cropwell Bishop Formation is the abundance of amorphous, nodular and vein gypsum, with the occurrence of a thick gypsum bed, known as the *Tutbury Gypsum*, and a stratigraphically higher but more diffuse gypsiferous zone, in which some thick

(~0.5m) gypsum beds may occur, referred to the *Newark Gypsum*. Borehole and surface evidence reviewed below suggest that in places the Tutbury Gypsum, or other thick gypsum seams, locally crop out or shallowly underlie Quaternary drift deposits. Underground provings of cavities indicate concentrations of gypsum that have been partially removed by leaching, giving rise to potentially hazardous near-surface ground conditions discussed in Section 10.3. In addition, the Tutbury Gypsum has been extensively mined underground; these activities are summarised in Section 10.1.4.

*Details:*

Where at outcrop, the nature of the formation is revealed in ploughed fields by yellow-brown to red, clayey soils with abundant lumps or smaller flakes of bright red, rarely green, weathered mudstone and silty mudstone. In fields east of Hills Farm [5345 2509], a sequence estimated from mapping to be c. 4 m thick, just below the base of the Blue Anchor Formation, contains four thin (c. 0.2 m) beds of grey to green calcareous siltstone and fine-grained sandstone: lower beds of similar lithology form minor features and give rise to flaggy brash farther north [5350 2530].

There are very few exposures of the unit. In the deep railway cutting west of East Leake, a small section in a drainage channel [5445 2593] showed rather fissile red and green, calcareous mudstones beneath Quaternary glaciofluvial deposits, at a stratigraphical level close to the top of the formation. In a drain by the side of the new bypass road close to the former gypsum mine at Gotham [5339 2935], exposures showed about 0.7 m of massive gypsum with an irregular, karstified top surface infilled or draped-over by highly contorted, red and green laminated mudstone. The occurrence represents the top of a weathered and partially-dissolved gypsum layer, with cavitation followed by collapse of the overlying strata accounting for the latter's contortion.

A stream section near West Leake [5346 2714 to 5364 2722] exposed a few metres of strata near the upper part of the formation. Along much of the section the upper part of the exposure was thin drift composed of between 0.5 and 1 m of red-brown clay with sporadic pebbles and cobbles. The western, and lowest, part of the section comprised 0.5 m of weathered green-grey mudstone dipping about 2 degrees to the east. This passed up into red-brown mudstone with one thin lenticular bed of siltstone; at the east of the section, the beds appeared to be horizontal.

Non-confidential borehole records of the formation, of sufficient quality to be informative, are rare in the present area. Borehole No. 95, along the A453(T) south of Ratcliffe Power Station, showed the following sequence:

| *Lithology* | *To (depth from GL in m)* |
|---|---|
| Made Ground | 5.6 |
| **Cropwell Bishop Formation:** | |
| Clay, red with grey and green spots (weathered mudstone) | 6.3 |
| **Gypsum**, white (probable partly dissolved *Tutbury Gypsum*) | 7.65 |
| Mudstone, red-brown, silty, with fibrous gypsum veins and common white nodular gypsum bands up to c. 0.15 m thick | 20.5 |

Another record that gives details of the sequence comes from the record published by Sherlock and Hollingworth (1938, page 46) of a shaft sunk at Gotham (formerly Glebe) Mine, but the exact position of the shaft is not specified.

| *Lithology* | *To (depth from GL in m)* |
|---|---|
| Details of overlying sequence given to | |
| **Blue Anchor Formation**; recorded as 'Blue limestone' and | 24.99 |
| '[?base of tea-green Marl]' | 28.14 |
| **Cropwell Bishop Formation:** | |
| 'Soft marls' | 31.08 |
| 'One side soft marls, the other side hard marl' | 34.74 |
| 'Hard marl' | 41.76 |
| 'Gypsum stone' | 45.42 |
| 'Marl with ball gypsum and seams of gypsum' | 53.87 |
| 'Broke into mine at' | 64.31 |

The conclusion from their record is that here the sequence of the Cropwell Bishop Formation overlying the Tutbury Gypsum is 36.17 m thick. They also note that the Tutbury Gypsum is 2.44 to 3.35 m thick here, this combined with the 27 m thickness of strata below the Tutbury seam suggests a total thickness here of about 66.5 m for the Cropwell Bishop Formation.

Tutbury Gypsum

The Tutbury Gypsum has been mined extensively in the area, but all mining has now ceased. Because the rock dissolves at shallow depths, and because of the need to maintain a suitable thickness of cover rock, the mined area largely coincides with the higher ground composed of the Blue Anchor Formation or younger strata. Most of the high ground between Rushcliffe Lodge [548 276] and Hillside Farm [526294] has been undermined. A few areas outside of the crop of the Blue Anchor Formation have also been worked; there are ancient mine workings at shallow depth along the north-east side of West Leake Hills towards Gotham and small areas of worked ground south-west of the hills. Although it has been extensively exploited in gypsum mines, few details of the Tutbury Gypsum have been published since the work of Sherlock and Hollingworth (1938). Because gypsum is soluble in water, the Tutbury seam has been largely dissolved away at and near outcrop, the depth of extensive dissolution commonly penetrating to 20 or 30 m. No exposures of it were seen in this area during the resurvey and its outcrop, depicted on the accompanying map, is based mainly on extrapolations from subsurface information. The details given below, mainly taken from Sherlock and Hollingworth, are generally substantiated by commercial borehole information, some of which was logged by R.G.Wyatt in 1961.

Where the Tutbury Gypsum has not been thinned by dissolution, the seam ranges from about 3 to 5 m in thickness with an average of about 4 m. The seam comprises mainly white to pale pink and grey nodular and massive gypsum with abundant fibrous gypsum veins and variable amounts of marl that in some places form a bed. Boreholes and mineworkings show that the main seam is overlain by a thin persistent unit (0.3-0.6 m) of red-brown mudstone. This is in turn overlain by a persistent thin seam of nodular gypsum called the "roof ballstone". The "roof ballstone" is composed of white nodular gypsum in large nodules or balls, commonly 0.3-0.4 m across. It forms a competent unit that makes a strong roof to the modern mine workings, but it was commonly robbed when older mine workings were abandoned (Sherlock and Hollingworth, 1938). Some borehole records, abandonment plans and descriptions by Sherlock and Hollingworth record that a second "ballstone" also occurs about 2 m above the "roof ballstone"; further details of this are given below.

*Details:*

The plan for the Winsor and Coy Gotham Gypsum Mine (Abandonment Plan No. 3592) has a section through the Tutbury Gypsum seam as it was worked, on the flank of the West Leake Hills, between Hillside Farm and Gotham [527 294]. Only 5 feet (1.52m) of "gypsum and coarse stone" was recorded in the bottom part of the seam and it is possible that parts of the seam hereabouts have been thinned by dissolution. The section noted on the plan was:

| | *Thickness (m)* |
|---|---|
| 'Red marl to surface' | |
| 'Gypsum, 10 inches' | 0.25 |
| 'Red Marl, 5 feet' | 1.52 |
| 'Gypsum, 1 foot 6 inches' | 0.46 |
| 'Red Marl, 1 foot 6 inches' | 0.46 |
| 'Gypsum and Coarse Stone, 5 feet' | 1.52 |

A similar section through the seam was also presented on the abandonment plan for the former Gotham Gypsum Mine [350 292] owned by J Cartwright and abandoned in 1899 (Abandonment Plan Number 3978).

This plan, by the same mining engineer as the one for Windsor and Coy noted the following section:

| | *Thickness (m)* |
|---|---|
| '2nd Ball, 1 foot' (gypsum) | 0.30 |
| 'Red Marl, 8 feet 6 inches' | 2.59 |
| '1st Ball, 2 feet' (gypsum) | 0.61 |
| 'Red Marl, 3 feet 9 inches' | 1.14 |
| 'Gypsum' | 1.52 |

Like the section recorded immediately to the north, the thickness of the massive gypsum in this record is much less than that proved in the deeper boreholes and mineworkings to the west of this site; this thinning may be the result of gypsum dissolution.

The description of the Tutbury Gypsum given for Glebe Mine [c.537 289] by Sherlock and Hollingworth (1938, p 46) noted that it was 8 to 9 feet (2.44-2.74 m) thick, increasing to 10 or 11 feet (3.05-3.35 m) in places. They also noted that:

"The main seam contains veins of fibrous gypsum and 'stringers' of marl in places. The surface of the seam is gnarled. The sequence of beds above the main seam is: red marl 3 ft.

(0.91m); cakes of gypsum (1st ball); red marl, 2ft. (0.61 m); another layer of gypsum cakes (2nd ball). The 1st ball is also extracted, but not the 2nd ball.

The gypsum is for the most part of good quality, although some cheaper grades are also produced. A little blue anhydrite occurs as cores in the blocks of gypsum."

A description of the Tutbury Gypsum at Kingston Mine [5247 2873] was also given by Sherlock and Hollingworth (1938 p.49) who described it thus:

"Here the seam of the Gotham district is about 8 ft. (2.44 m) thick, and is said to be made up of 'bullets' with 'fault', *i.e.* gypseous marl, between. The 'fault' may be as much as 10 or 15 ft. (3.05-4.57 m) wide between the 'bullets', with second-grade gypsum between. White gypsum called 'pottery', is found at the top and bottom of the 'bullets', with second-grade gypsum between. The bottom of the seam, below the 'bullets', is third grade. Cakes above the seam are also worked, but not regularly, and are the best stone. Another seam about 10 ft. (3.05 m) above them is not good and is not worked."

This description merits some interpretation to put it into a modern descriptive framework. The 'bullets' of gypsum are probably the massive gypsum that has not been dissolved. The 'fault' between the 'bullets' is probably collapsed material that has fallen into the spaces left after the dissolution of the gypsum. This pattern of undissolved blocks surrounded by foundered material is common in gypsum seams at fairly shallow depths. The white gypsum called 'pottery' is probably a fairly pure gypsum at the top of the main gypsum masses. The 'cakes' above the seam are probably the nodular 'roof ballstone' referred to in the descriptions above. The descriptions of first, second and third grade gypsum refer to the amount of impurities in the rock, firsts may be suitable for alabaster, seconds for plaster and thirds for inferior plaster and agricultural use.

Newark Gypsum

The Newark Gypsum is very poorly exposed and much of the gypsum within it has been dissolved so that details of it are scant. In boreholes it is shown to be several layers with concentrations of gypsum nodules rather than a proper seam. The nodules can be up to a metre or so in size, but 0.2-0.5 m is a more common size and concentrations of much smaller nodules are also present. The thickness of strata over which these nodules are concentrated appears to be around 5-8 m, their base lies at about 18 m above the top of the Tutbury Gypsum and 20 m below the base of the Blue Anchor Formation.

*Details:*

The Newark Gypsum has not been extensively mined, but the plan for the former Winser and Coy Gotham Gypsum Mine, abandoned in 1896 (Abandonment plan number 3582) gives some details. The area worked in this seam was very small and amounted to approximately 200 m by 100 m situated about 150 m east-south-east [528 293] of Hillside Farm. The mine plan shows that the "Top Seam" was 5 feet (1.52 m) thick composed of "gypsum in balls" surrounded by marl. This description accords with the nodular nature of the seam recorded elsewhere.

R L Sherlock (MS fieldslip N50NW/W) reported a former gypsum mine, possibly exploiting the Newark Gypsum, located not far below the inferred junction with the Blue Anchor Formation, in ground now used by the Rushcliffe Golf Course [5498 2795]. It consisted of a 20-30' (6.1-9.1m) deep cut in 'red marl with a few broken gypsum bands and gypsum lumps two thirds of the way down'.

5.3.6. Blue Anchor Formation

The term Blue Anchor Formation was introduced and defined by Warrington et al. (1980) to describe a widespread sequence of distinctive grey and greenish-grey mudstones occurring immediately beneath the Penarth Group throughout England and Wales. In those parts of the Melton and Loughborough districts covered by the present map sheet, this unit is predominantly green and was formerly called the 'Tea-green Marl' (Fox-Strangways, 1905; Lamplugh et al., 1909).

The formation was formerly thought to be of Rhaetian age (Warrington et al., 1980), but now its middle to lower part is believed to be Norian (Oral communication, G W Warrington, 1996).

The base of the formation is marked by a colour change from the red-brown and deeper grey-green mudstone of the Cropwell Bishop Formation. Confidential borehole records for gypsum exploration suggest that the thickness of the formation varies between 7 and 10 m across the area.

*Details:*

The formation crops out in a narrow zone beneath the Penarth Group in the West Leake Hills and on Winking Hill [5135 2965]. It also forms small outcrops on the western outskirts of East Leake [546 262] and near the southern map sheet margin [5345 2502]. Its presence is most commonly revealed in ploughed fields by the presence of greenish grey, clayey soils that contain abundant flakes and larger fragments of distinctive pale green mudstone; in the field east of Hills Farm [5345 2502], rain-wash following ploughing had removed the topsoil, baring the *in situ* weathered green mudstone over an appreciable area.

Exposures are mainly confined to man-made cuttings or areas of bared ground in ploughed fields (see above), or footpaths. In a culvert on the side of the disused railway cutting near East Leake [5454 2608] green mudstone was visible for several cms beneath glaciofluvial sand. Up to 1 m of the unit was seen in excavations for a recently-completed path through the wood on Rushcliffe Golf Course [5429 2813]: it was a green, blocky and dolomitic mudstone, with no obvious sedimentary structures and with no variation in lithology. Further exposures were seen farther south on the Golf Course, by the side of the path winding down the slope from the Club House [5484 2784].

On the steep flank of Winking Hill [5178 2973] the soil is pale grey and greenish brown becoming red-brown on the lower part of the slope. Numerous auger holes up the bank here penetrated about 1m of loose soil-creep material and entered grey-green mudstone. The estimated thickness of the grey-green mudstones here was about 7 m.

Near Whitehills Farm [528 283] the low rounded ridge at the foot of the West Leake Hills is composed of grey-green mudstone and siltstone that weather to a pale grey and greenish brown soil. Auger holes here show that pale green siltstone is present at shallow depth.

## 5.4. Penarth Group

Warrington et al. (1980) introduced the term 'Penarth Group' as a substitute for the term 'Rhaetic'. Increasing confusion over the status of the latter term had arisen due to its use in both a litho- and chronostratigraphical context. The Penarth Group, as defined in the Nottingham district (Howard et al., in prep.), corresponds exactly with the 'Rhaetic' of the primary geological surveys (Fox-Strangways, 1905; Lamplugh et al., 1909). The boundaries of the group do not, however, coincide with those of the Rhaetian Stage. This encompasses strata between the middle of the underlying Blue Anchor Formation (Mercia Mudstone Group) and the lowest part of the Barnstone Member (Lias Group) (Oral communication, G W Warrington, 1996).

The base of the group is not exposed in the present area. Elsewhere it is sharp and represents an interruption in deposition, with distinctive dark fissile mudstones at the base of the group, and locally a bone-bed, overlying the bored and mudcracked upper surface of the Blue Anchor Formation (Kent, 1968). The group varies between 0.6 and 16 m thickness around Nottingham (Kent, 1968), and from borehole data is suggested to be between 9 and 13 m thick in the West Leake map sheet.

Two subdivisions of the Penarth Group, the Westbury and Lilstock formations (Warrington et al., 1980), are recognised in adjacent areas (Howard, 1989; Brandon, 1994). In the present area they form subdued features on the less-steep slopes and so can be mapped out, although they are very seldom exposed.

### 5.4.1. Westbury Formation

The Westbury Formation consists principally of dark grey to black fissile mudstones with very thin beds of sandstone and siltstone at some levels. The well known 'Rhaetic Bone Bed' occurs either at, or just above, the base of the formation around Nottingham, but is impersistent (Sykes et al., 1970): in the adjacent sheet to the south Brandon (1994) thought it was largely absent, though noting an account of one specimen which previous workers had recovered from a spoil heap. An impoverished bivalve fauna indicative of marine environments occurs at some levels.

*Details:*

The Westbury Formation is not exposed in this area. Where it crops out around the West Leake Hills (e.g. north-west of East Leake), its base commonly coincides with a concave feature marking a change to steeper slopes leading up to the Lias Group outcrop. On the particularly steep slopes south of Fox Hill Farm [5425 2689], the presence of the unit is revealed by abundant flakes of black to dark grey, silty mudstone brought up by animal burrowing. On the north-eastern slopes of the West Leake Hills, on the footpath from Gotham [5346 2888], animal burrows reveal brown, weathered mudstone while brash nearby indicates the presence of buff, medium-grained sandstone beds within the sequence.

On the flank of Winking Hill [5178 2975] the sequence of auger holes that prove the Blue Anchor Formation also prove the contact with the overlying Westbury Formation. They penetrated a thin sequence of glacial till with abundant fragments of dark grey mudstone.

5.4.2. Lilstock Formation

Warrington et al. (1980) recognised two members within the Lilstock Formation. The lower member (Cotham Member) is well developed in the present area. The upper division (Langport Member, or 'Sun Bed' of Trueman, 1918) is not recognised, although it does occur - as a 0.25 m bed of micritic limestone - in the adjacent area to the south (Brandon, 1994).

In the Nottingham district, the Cotham Member consists of pale grey to greenish grey, blocky and silty mudstone with small irregular limestone nodules; at the top it includes a greyish-brown to bluish-grey porcellanous nodular limestone up to 0.15 m thick (Sykes et al., 1970). Its base is gradational, and characterised by an upward transition from fissile to blocky bedding, from dark grey to pale greenish grey colour, and an increase in the carbonate content.

In the present area, the Cotham Member is seldom exposed, nor are there any useful descriptions in the gypsum exploration borehole logs. From feature mapping, however, the unit is estimated to be about 4 m thick.

*Details:*

The only exposure of the member was seen in a cutting behind a shed at the Rushcliffe Golf Course [5495 2782]. It consisted of about 0.7 m of brown to grey, blocky mudstone.

Fox-Strangways (1905, p.35) mentioned former excavations exposing dark laminated shales with *Avicula contorta* and other bivalves, at the 'north end of Ash Spinney' [5346 2758] and in a ditch at the east end of Crownend Wood [5289 2854]. At the latter locality he further recorded 'the band of nodular septariform limestone......marking the upper portion of these beds', seemingly confirming that these exposures must have been in the Cotham Member.

## 6. JURASSIC

### 6.1. Lias Group

6.1.1. Scunthorpe Mudstone Formation - Barnstone Member

In the East Midlands, the lowermost part of the Lias Group consists of grey limestone and interbedded calcareous mudstone, formerly termed the Hydraulic Limestone (e.g. Fox-Strangways, 1905; Lamplugh, 1909). In a recent review of the stratigraphy of the lower part of the Lias Group in the East Midlands, Brandon et al. (1990) have renamed these beds as the Barnstone Member, the lowermost division of the Scunthorpe Mudstone Formation. In the East Midlands as a whole, the member varies from 6 to 9 m thick (Swinnerton and Kent, 1949).

In the Loughborough district, as elsewhere (Trueman, 1918, p.66), the lower part of the

Barnstone Member is devoid of ammonites, although a marine bivalve fauna is present. The name 'Pre-Planorbis Beds' has been assigned to these strata (Trueman, 1915; Kent, 1937) and remains a useful informal descriptive term. As the base of the Hettangian - and hence the Lower Jurassic - in Britain is taken at the lowermost occurrence of ammonites of the genus *Psiloceras* (Cope et al., 1980), the 'Pre-Planorbis beds' are assigned to the uppermost Rhaetian Stage of the Triassic. In the adjacent map sheet to the south, these latter beds are 2.92 m thick (Brandon, 1994), but due to lack of exposure they have not been recognised here.

In the present area the Barnstone Member is the youngest Solid unit to occur at outcrop, or at rockhead beneath drift. It occurs as outliers which form flat, plateau-like tops to the West Leake Hills and Winking Hill. Since erosion has removed the softer Lias Group beds, that formerly overlay the member, the present plateau surfaces (where not drift-covered) must correspond closely to the top surface of the member. On this basis the Barnstone Member is estimated to have a thickness of just over 9 m.

*Details:*

The base of the Barnstone Member corresponds to the main convex break of slope which can be traced all around the West Leake Hills, just below the plateau rim. No top to the unit is present, but a prominent crest, representing the margin to the topmost limestone bedding plane, forms the actual plateau rim. In fields both on and below this feature, there occur abundant brash of flaggy, grey to white, micritic limestone in a dark grey to brown, clay-rich soil.

The Barnstone Member was formerly worked in a few small quarries on the plateau surface of the West Leake Hills. At one such site, location unspecified (possibly [5354 2812] from his MS fieldslip L10NE/NE), Fox-Strangways (1905, p.38) mentioned the presence of 'seven or eight' very flaggy limestone beds, with abundant fossils of *'Ostrea liassica'* on bedding planes. Observations by R L Sherlock (MS fieldslip N50NW/W) at two backfilled quarries south of Rushcliffe Golf Course [5472 2764 and 5462 2732] indicated alternations between beds of flaggy limestone, between 2' and 18" thick, and brown, weathered mudstone: limestone bedding surfaces contained *Ostrea liassica* and *Modiolaris minima.* A further small quarry to the south is also backfilled, but there is much spoil of flaggy limestone still to be viewed. The fragments are tabular, between 20-80 mm thick, show gently undulating bedding and lamination, and some have beddings planes crammed with shell debris. A specimen of the latter (JNC 814) was reported on by B M Cox (Written communication, 1996). It consists of shell-fragmental packstone with a brownish grey microcrystalline matrix and some laminae of pale grey argillaceous micrite, the latter being particularly distinctive of the Barnstone Member. The fauna includes common *Liostrea*, a pectinid (?*Pseudopecten)* and abundant echinoderm fragments.

## 7. QUATERNARY DEPOSITS

### 7.1. Till

Diamictons representing various ill-sorted products of former ice sheets, form scattered outcrops capping the bedrock across the south-western part of the area. The till lithologies are typically heterogeneous, stony and sandy clays and are likely to include both ground moraines (lodgement tills) and flow tills. Some earlier geological surveys in this region mapped till outcrops largely on the occurrence in soils of exotic brash, of which the rounded 'Bunter' pebbles and angular flints are perhaps the most prominent. This present study found that brash is at best indicative, and at worst a misleading criterion on which to base drift boundaries. For example, augering reveals that such brash commonly reflects the presence of thin (~0.2-0.4 m) deposits of sandy head or till *remanie*, which are too small and intricate to be mapped separately. In this study, therefore, the field mapping of till boundaries has been mainly constrained by geomorphology, augering and the close examination of exposed sections, combined with the observation of small-scale features.

7.1.1. Thrussington Till

This is the only till variety recognised in the area It contains material of mainly Triassic or Carboniferous derivation, and was deposited from ice that advanced from the north and west (e.g. Rose, 1994).

*Details:*

Substantial spreads of Thrussington Till overlie Mercia Mudstone bedrock to the south of the Kingston Brook. Ploughed fields on the outcrops typically reveal a heavy, yellow-brown to brown-red soil with abundant 'Bunter' quartz and quartzite pebbles together with fragments of Carboniferous sandstone, Carboniferous Limestone [e.g. 5420 2575] and rare flints. The occurrence of flints, together with minor chalk debris at one place [5226 2533], may suggest that locally the Thrussington Till is mixed or has 'hybridised' with north-easterly derived Oadby Till; however, such deposits proved impractical to map out at the time the survey was conducted.

Exposures of Thrussington Till are uncommon. At the bottom of the disused railway cutting close to the Woodgate Road bridge [5427 255], scars showed a tough, red to brown clay with common 'Bunter' pebbles, the depth of the cutting here indicating a till thickness of at least 10 m. A further exposure of red stony clay with 'Bunter' and flint pebbles occurs in old workings east of St. Anne's Manor [5120 2520].

That the Thrussington Till has in part infilled pre-existing valleys, which are now being re-exhumed, is indicated by local variations in the rockhead elevation at the base of the till sheet. For example, mapping shows that the till base to the north of the Kingston Brook slopes southwards towards the valley bottom, declining from 90 m above OD to less than 80 m south of Fox Hill Farm [544 272]. Till to the south of the brook slopes northwards towards the valley, its base declining from about 66 m above OD in the south [5383 2560] to just over 55 m farther north [5415 2606].

The till also caps the west end of Winking Hill [5151 2980] where it comprises a red-brown clay with abundant rounded pebbles and numerous angular fragments of limestone derived from the Barnstone Member. Similar till with abundant pebbles and cobbles of Carboniferous sandstone and 'Bunter' Quartz also overlies the Barnstone Member on the southern part of the West Leake Hills around Stone House [5386 2792].

## 7.2. Glaciofluvial Deposits

These unconsolidated sands and gravels represent the deposits of stream channels or outwash fans derived from melt waters that either flowed beneath or discharged from the front of the ice sheets.

*Details:*

Glaciofluvial deposits probably do not exceed 2-3 m in thickness in this area (but see below). Those occurring beneath the Thrussington Till form patchy outcrops. These include that to the south of Landcroft Lane [5185 2570], where a low, ridge-like feature is underlain by light sandy soils with abundant 'Bunter' pebbles, below which was augered brown to red, medium-grained pebbly sand: the isolated outcrop farther west [508 257] may be an outlier of the same deposit.

A further development of sub-Thrussington Till sand and gravel, that may be up to 4 m thick, underlies the lower-lying part of East Leake in the extreme east of the area. In terraced ground for a plant nursery [5500 2570], poor exposures indicate the presence of red to brown sand with abundant 'Bunter' pebbles, about 20 % flints and sporadic fragments of red Triassic mudstone. This deposit can be traced to the north-west, appearing as medium-grained pebbly sand above Trias strata in drainage channels down the side of a disused railway cutting [5454 2608]. Glaciofluvial deposits that underlie Thrussington Till west of Fox Hill Farm may have been formerly worked south of the track [5380 2701], where scars show crumbling exposures of yellow sand; a nearby (confidential) borehole indicated 3.7 m of 'Boulder clay & bands of gravel', above bedrock.

An extensive spread of glaciofluvial deposits, which partly underlie Thrussington Till, caps the ridge around and to the east of Manor Farm [533 260]; the fact that the base of this deposit lies at about 50 m above OD and its eroded top surface at 62 m would, assuming a flat lower boundary, suggest a thickness of around 10 m. In scars by a track [5351 2589] the deposit consisted of brown, medium-grained sand with sporadic pebbles (c. 15%) mainly of 'Bunter' quartz. Farther east, the base of this deposit falls to 45 m along the south side of the Kingston Brook [540 2636], thus behaving similarly to the overlying Thrussington Till's base (Section 7.1.1.).

Two areas of Glaciofluvial deposits cap the hills to the north and west of East Leake. At Moulter Hill [521 269] the deposit appears to be about 10 m thick. It is composed of sandy gravel with pebbles and cobbles dominantly of Carboniferous sandstone, plus about 10% of quartz pebbles and 10% of mixed lithologies including flint and volcanic rocks. On the hill north of West Leake [527 269] the deposit is at least 6 m thick and of similar lithology to that at Moulter Hill.

## 7.3. River Terrace Deposits

These mainly comprise sand and gravel and represent the cold stage aggradations of the river Soar and its tributaries, terraced by later valley incision. The older deposits may also have been substantially altered by various periglacial processes. The Soar terrace deposits are contiguous with those farther west, the nomenclature and lithology of which are described in Brandon and

Carney (1997). The report of Brandon (1996) gives correlations and discusses the ages of the Soar and neighbouring Trent terraces.

7.3.1. Birstall Sand and Gravel

This high terrace is possibly represented by sands and gravels capping bedrock between Kingston on Soar and Sutton Bonington, possibly extending eastwards to East Leake. The deposit is thought to be coeval with the Eggington Common Sand and Gravel of the River Trent and is of probable late Wolstonian age (Brandon, 1996).

*Details:*

The outlier at Station Plantation [5035 2720] has been worked in a series of small pits on either side of the road, and is probably over 3 m thick. It has a base at about 38 m above OD, which is about 6 m above the floodplain of the River Soar. A larger terrace remnant underlies the Sutton Bonington Agricultural College campus [256 262] and extends eastwards to Dimleo's Spinney [5140 2638]; a further outlier occurs to the east [5235 2604]. These last three outcrops rest on a base which overall declines gradually towards the Kingston Brook, from about 45 above OD at Sutton Bonington Campus to 43 m at the crossroads [5241 2610] just above the brook. The soils on these various outcrops are light and pebbly, consisting of abundant 'Bunter' quartz and flints (~15-20%). An excavation for a new building at Sutton Bonington Agricultural College [2562 2615] showed about 1.4 m of yellow, medium-grained clayey sand with common Bunter pebbles and flints, resting on red blocky mudstone of the Gunthorpe Formation.

Farther east, on the southern side of the Kingston Brook, the wide flats which extend into East Leake village are tentatively correlated with the Syston Sand and gravel. The base of the deposit lies at 46 m above OD and is separated from the Kingston Brook floodplain by a c. 2-3 m high bedrock step [5470 2650].

7.3.2. Wanlip Sand and Gravel

This terrace deposit is restricted to narrow flats bordering the River Soar and some of its tributaries between Sutton Bonington and Ratcliffe on Soar. It correlates with the Beeston Sand and Gravel of the River Trent and the Allenton Sand and Gravel of the River Derwent, and is thought to be lower to mid-Devensian in age (Brandon, 1996). An extensive terrace at Kingston Park has also been included in this terrace; it stands higher than the Syston Terrace that abuts it and has a similar elevation to the deposits mapped to the north-west. However, it is much more extensive than deposits of this terrace mapped elsewhere.

*Details:*

A narrow but pronounced terrace bordering the River Soar, to the west of the Agricultural College, is correlated with the Wanlip Sand and Gravel: its base lies at about 35 m above OD, and it is separated from Soar alluvium and Older Alluvium by a 3 m high bedrock step. Animal burrows along the front terrace edge [e.g. 5009 2605] reveal yellow or pink fine sand with pebbles locally. Similar deposits were augered on the narrow terrace remnants at Kingston on

Soar [5012 2802] and south of Ratcliffe on Soar [5003 2867].

The extensive terrace at Kingston Park forms a flattish area (elevation 36-38m) between the lower land of the Syston Terrace and alluvial deposits to the south-west and Older Alluvium to the north-east. The deposit comprises brown clayey sand with pebbles and a few cobbles, the clasts being dominantly composed of Carboniferous sandstone with lesser amounts of vein quartz. One auger hole[5158 2773] near the north-east margin of the deposit proved a feather edge of clayey sand up to 0.5m thick resting on weathered bedrock of stiff red-brown slightly sandy clay. From this information the terrace deposit appears to be 1-2m thick.

7.3.3. Syston Sand and Gravel

This deposit forms a low-lying terrace at the eastern edge of the Soar valley c. 0.4-1.0 m above the Older Alluvium and up to 1.5 m above the floodplain of the Kingston Brook around Kingston on Soar [503 276]. In the adjacent sheet to the west the deposit was interpreted as the periglacial, fluvial, braid-plain equivalent of a valley sandur (Brandon and Carney, 1997). It forms a relatively shallow infill, compared with other terrace deposits, and may not underlie Older Alluvium.

*Details:*

At the Kingston on Soar locality mentioned above, the front edge of the Syston Terrace is highly degraded, and only about 1.5 m above the modern floodplain that here is estimated to be about 32-33 m above OD: there is no intervening bedrock step. It is noticeable that south of the Kingston bridge, flood defences bordering the east side of Gotham Road terminate by abutting the terrace edge, suggesting that the Syston Terrace is normally not overtopped during flooding at this point. In ploughed fields by Church Farm [5019 2786] augering showed brown, fine-grained sand with sporadic, small 'Bunter' quartz pebbles. The Syston Terrace feature is tentatively correlated with the narrow flats most prominently displayed along the northern border of the Kingston Brook floodplain, for example at West Leake [5255 2637], where the soils are light and sandy with abundant 'Bunter' quartz pebbles. In the main Soar valley, to the south-west of the area [5010 2505], the Syston Terrace forms a low, degraded flat whose top is ridge and furrowed.

7.3.4. Older Alluvium

The deposits known as Older Alluvium equate to those of the Hemington Terrace of the Trent valley (Brandon and Carney, 1997). They are interpreted to have been laterally accreted at channel point bars by successive meanderings of the River Soar from possible Late Glacial times into the late Flandrian (e.g. Brandon, 1996).

The village of Sutton Bonington is built on an Older Alluvium terrace flat, the surface of which lies at about 34 m or 0.5-1.0 m above the modern floodplain alluvium [503 254]. The terrace does not present sharp or well-defined front edges; instead, mapping suggests it is dissected by shallow channels of the modern alluvium, which its deposits probably at least in part underlie. A borehole (No 71) on one such alluvial channel, close to the margin with Older Alluvium showed the following sequence:

| *Lithology* | *To (depth from GL in m)* |
|---|---|
| Clay, green-brown, slightly sandy with some fine gravel | 1.8 |
| Clay, silty, with gravel | 1.9 |
| Gravel, brown, fine to coarse, very sandy | 3.7 |
| Silt, red-brown, clayey, with gravel size lithorelicts (weathered Mercia Mudstone?) | 4.5 (EOH) |

The bipartite division of this deposit into a clayey upper part and gravelly lower part is similar to that described for Older Alluvium in the adjacent area to the west (Brandon and Carney, 1997); however, given the location of the borehole, part or the whole of the upper clayey layer may also be made up of modern alluvium.

Older Alluvium also forms an extensive flattish area to the south-east of Ratcliffe on Soar Power Station. The deposit extends to the south-east past Kingston Fields Farm [515 280]. This deposit is composed of dark reddish-brown and grey brown clay, which in some places is very organic-rich. A ditch section in the deposit [5069 2887] showed dark brown clay to 1.3 m with a few pebbles and cobbles locally concentrated in a layer at a depth of about 1m.

### 7.4. Lacustrine Deposits, Undifferentiated

These deposits floor the western part of the large depression known as Gotham Moor, forming extensive flats lying at 33 m above OD. They probably originated during the periodic filling and drying out of a shallow lake. There are several similar recent lacustrine basins bordering the Trent in this region. That described by Champion (1969), forming Sinfin Moor to the north of the Trent, showed ages indicative of lacustrine deposition occurring as early as Pollen Zone VII B or Zone VIII of the Flandrian, probably post-Iron Age. A more recent study of the former Tollerton Lake, east of the present area, suggests that it commenced during locally high water levels around 10 200 BP and persisted until c. 7000 BP (McMurray, 1993). The Tollerton depression was thought to have originated as a result of lowering of the ground by the dissolution of underlying gypsum layers. Such an origin is possible since it is estimated that the outcrop of the Tutbury Gypsum, or its dissolved equivalent, may closely approximate to the present surface level of Gotham Moor.

*Details:*

East of Gotham the lacustrine deposits are in contact with head or Mercia Mudstone, the junction being poorly defined and marked by a change in soil type accompanied by an almost imperceptible break in slope. The deposits produce a black, organic-rich sandy clay soil which is locally abundant in mollusc and bivalve shells. Ploughing in fields south of Moor Lane [5442 2970] additionally produced slabs of dark grey, well-laminated silty clay and silty sand with bivalves. In a drain to the north [5444 2976] was exposed at least 1 m of pale greenish grey, organic-rich silty clay with abundant nodular to amorphous patches of cream to white ?tufa. A detrital component to these deposits, possibly indicative of gravel lenses, is suggested by the occurrence of locally abundant 'Bunter' quartz pebbles in patches of dark grey, organic-rich sandy soil [5440 2958].

The best exposure of these deposits occurs in a cutting for a horse-jump [5471 2954], where the following section was measured:

| *Lithology* | *Thickness (m)* |
|---|---|
| Sandy clay, red, structureless, with brick fragments (Made Ground) | 0.5 |
| Clay, silty, red-brown with ochreous mottles, structureless, grades to: | 0.08 |
| Clayey silt, black, structureless, organic-rich with shell fragments | 0.06 |
| Silt and clayey silt, black, organic-rich, structureless, with shells and abundant white tufa patches; some ochreous mottling | 0.37 |
| Sand, pebbly, clayey matrix, olive-green to brown-mottled, structureless, with dispersed small 'Bunter' quartz pebbles and subangular micritic Jurassic limestone fragments | 0.2+ |

### 7.5. Alluvium

Alluvium represents the detritus recently deposited by fluvial activity along the floodplains of modern drainage systems. It typically consists of a lower basal layer of sandy gravel, representing deposits by traction currents in channels, and a capping of clayey silt which represents the fine-grade overbank deposits of flooding events. In the present area the alluvium of the River Soar is represented in the west, but most of the alluvial tracts are those flooring the tributary valleys of that river.

*Details:*

In the south-western corner of the map sheet, alluvium of the River Soar is confined to a narrow channel, between 70 and 200 m wide, which appears to have exploited a junction between Syston Sand and Gravel and Older Alluvium. A drain [5008 2934] showed at least 1 m of dark brown to grey, loamy silt. The clayey deposits encountered in the upper part Borehole No. 71 farther north (see Section 7.4.4.) may also be attributed to modern alluvium.

The alluvium flooring the tributary valley of the Kingston Brook forms tracts which in places are up to 400 m wide. An exposure in a stream bank [5139 2680] showed 1.4 m of brown clay resting on at least 1.7 m of sandy gravel. Farther upstream, Borehole No. 28 through this alluvium showed the following:

| *Lithology* | *To (depth from GL in m)* |
|---|---|
| Fill | 0.6 |
| Clay, silty and organic, with pebbles and shell fragments | 1.21 |
| Clay, silty, brown-grey, very soft | 2.11 |
| Gravel, well-graded and sandy | 4.11 |
| On weathered Mercia Mudstone...... | |

The topmost bed in this section suggests that the Kingston Brook may locally have supported small lakes in the recent past.

A sequence indicative of alternations between head and alluvium deposition is shown by a further section in the Kingston Brook [5455 2668], south of the steep, head-mantled slopes of the West Leake Hills:

| *Lithology* | *Thickness (m)* |
|---|---|
| Soil | 0.05 |
| Sand, pebbly, brown (alluvial) | 0.04 |
| Clay, brown, with sporadic 'Bunter' pebbles and flints (soliflucted head) | 0.9 |
| Gravel (alluvial) | 0.1+ |

### 7.6. Head

Head is a slope deposit formed mainly by processes of solifluction and gelifluction. Although colluvium or surface hill wash, included here as head, has largely been produced by the stripping of vegetation by arable farming, solifluction and gelifluction are processes that mainly operated during the periglacial phases of the late Devensian. The nature of the head mainly depends on the lithology of the bedrock or superficial deposits developed upslope. It is generally a poorly-structured deposit but can retain relic shear zones in some circumstances. These may adversely affect its geotechnical properties and be a potential hazard to construction.

In this area, head deposits mainly occur along the lower parts of the steeper hill slopes, and in the intervening valleys. The upper boundary of the head is commonly a well-marked concave slope-break, but its distal boundary, when abutting alluvium or river terrace deposits, is less obvious and placed at the point where it is considered to merge with the flat-lying valley floors. Where valley alluvium is sparse, or the stream canalised or culverted, head commonly forms most of the upper part of the infilling deposit and can be exposed in the river banks.

*Details:*

Head composed of grey to brown sandy clay with sporadic 'Bunter' quartz pebbles and fragments of Jurassic limestone extensively mantles the southern slopes of the West Leake Hills, and is commonly exposed in small scarplets caused by local landslippage [5449 2683]. This head aprons out onto the valley floors below, and in the banks of the Kingston Brook is locally seen as clayey layers which alternate with sandy or gravelly alluvium (see above section).

A more sandy type of head, derived mainly from glaciofluvial deposits, is commonly encountered in the area. On the slopes below Manor Farm, the sides of a sunken lane [5316 2626] expose red, clayey and pebbly sand probably representing an admixture of material derived from glaciofluvial deposits and the Cropwell Bishop Formation. Pebbly sand forms an extensive veneer largely masking the Mercia Mudstone between Kingston on Soar and Sutton Bonington; its thinness is commonly revealed by the appearance of mudstone fragments in soil, and in rare excavations, one of which [5059 2688] shows 0.6 m of sandy head on the bedrock. The presence of this head is largely responsible for the exaggerated outcrop of 'Fluvio-glacial gravel' shown to the north of Sutton Bonington on the earlier 1:50 000 scale Loughborough map.

On the flank of Moulter Hill [5182 2667], the head deposit is also largely derived from the glaciofluvial sand and gravel deposits that cap the hill. It forms a concave slope down to the alluvial and terrace deposits below. The head is composed of brown sand and clayey sand with pebbles and has a stone content similar to the glaciofluvial deposits.

Head which is composed of red silty clay with pebbles is more typical of the deposits developed on the lower parts of slopes underlain by Mercia Mudstone and/or Thrussington Till, as seen in a drain north of Brickyard Lane [5355 2549]. A similar type of head forms an extensive, low-lying fringe to the southern part of Gotham Moor, where it is overlain by glaciolacustrine deposits: in a drain south of the disused railway crossing the Moor [5427 2947], it consisted of 0.5 m of red, silty clay with sporadic pebbles underlain by at least the same thickness of green to grey pebbly clay. This particular expanse of head fills a shallow valley originating from a bowl-shaped embayment on the eastern flanks of the West Leake Hills; the soils on this head are brown, clayey and silty with sporadic Bunter pebbles, derived from Thrussington Till, and fragments of Jurassic limestone derived from the Barnstone Member outcrop.

### 7.7. Landslip

Landslippage is detected by the observation of anomalous features which denote the downslope movement of rock strata or superficial deposits. In the present area, slope instability is suggested by terracettes parallel to the contours of the steep, southern slopes of the West Leake Hills, to the north of the Kingston Brook [5455 2685]. The terracettes locally expose clayey head (see above section), suggesting that the slippage occurred within the superficial deposits. Above the terracettes there is a narrow ledge-like feature, marking the upper boundary of the landslipped area. Its position appears related to the outcrop of the Cotham Member, and so it may represent a slumped block of the latter, mantled by head.

## 8. STRUCTURE

Most of the structures recognised in the area post-date at least the Triassic and in some cases the Lower Jurassic. Many faults are probably the rejuvenations of important structures dating back at least to Lower Carboniferous times.

### 8.1. Lower Carboniferous Structure

From early Dinantian to early Namurian times the *Normanton Hills Fault* (or Hoton Fault), located in the south-west of the area, acted as a major control on sedimentation (e.g. Ebdon et al., 1990). It formed the south-western margin to the Widmerpool half-graben ('Gulf'), in which was accumulated several kilometres of basinal-facies sediments, the younger part of which is represented by the Long Eaton Group and Widmerpool Formation sequences of the Ratcliffe on Soar Borehole (Figure 2). The succeeding Edale Shale Group, of Namurian (Pendleian) age, is considered by Ebdon et al. to represent a later stage of passive thermal subsidence in the region, when fault movements had largely ceased and the half-graben was being progressively infilled.

## 8.2. Post-Triassic and post-Jurassic Structure

### 8.2.1. Stratal Dip

There are few direct measurements of strata exposed in the area. Estimates of regional dip based on borehole correlations, and using the Tutbury Gypsum as a structural marker horizon suggest that the strata are almost horizontal to the south-west of Gotham [around 595 252]. To the south-east, however, they may outline a broad, north-west trending syncline with an axis coinciding with the plateau surface of the West Leake Hills. The outcrop boundary of the Blue Anchor Formation at East Leake [5460 2622] is consistent with a gentle northerly to north-eastwards structural dip, consistent with that locality being situated on the southern limb of the syncline.

### 8.2.2. Faults

*West to north-west* trending faults and associated monoclines (see below) dominate the structure in the south-west corner of the map sheet. The principal displacement is the *Normanton Hills Fault*, along which an unspecified part of the Gunthorpe Formation is juxtaposed with the Cropwell Bishop Formation and Penarth Group, indicating a throw to the north-east of at least 150 m. A parallel fault, in part following the Kingston Brook, has been inferred farther to the north-east and is in large part extrapolated from the adjacent map sheet to the west; it has an antithetic relationship to the Normanton Hills Fault since it throws to the south-west. A further fault passing to the south of Kingston Fields Farm [5165 2792], has a north-easterly throw of probably between 2-5 m, from the limited borehole evidence available. A west-north-westerly fault throwing north-eastwards is inferred along the southern boundary to the Blue Anchor Formation at East Leake [5470 2587], although much of that area is covered by Drift deposits.

The north-eastern side of the West Leake Hills is also marked by a fault proved in the mine workings. On the original manuscript fieldslip for the Gotham area the fault is recorded with a downthrow to the south-west. In the workings of Glebe Mine [5368 2876] the throw is noted to be 9 feet (2.74 m), and in Cuckoo Bush Mine [5321 2909] it is 12 feet (3.66 m). This fault passes into a monocline with subordinate faulting as it continues to the north-west past Winsers Mines [5275 2947] to near Stonepit Wood [5238 3000] (see below).

### 8.2.3. Monoclinal flexures

Two of the normal faults mapped in the area have been shown to pass into monoclinal flexures proved in gypsum mine workings. To the north-east of the West Leake Hills the north-west trending fault passes northwards into a monocline proved in the workings to the north-east of Stonepit Wood [5238 3000]. Here it has an effective south-westerly downthrow of about 18 m.

South-east of the West Leake Hills the gypsum mine workings have proved another monoclinal structure, but with a north-easterly trend. The monocline here has a southeasterly downthrow of about 14 m which decreases to about 5 m in the south-west.

# 9. ARTIFICIAL DEPOSITS AND WORKED GROUND

This section describes ground, depicted on the accompanying 1:10 000 map sheet, changed because of human activities, the impact of which is detectable by surface or subsurface investigation.

*Worked Ground* corresponds to areas where the ground is known to have been cut away by man. In this area it mainly includes road and rail cuttings, small clay or gravel pits and ponds.

*Made Ground* comprises those areas where the ground is known to have been deposited by man. Road embankments, coal stockpiles and flyash spoil heaps of the Ratcliffe Power Station, the waste from former clay or sand pits, or from gypsum workings, and constructional fill associated with factory sites, sewage works and the Ratcliffe Power Station are the principal types of Made Ground in this area. River flood banks are generally too narrow to be included on the map.

Made Ground is a potential hazard to development. Its geotechnical properties are dependant on its composition, which is usually difficult to determine unless comprehensive records have been kept.

*Worked and Made Ground* covers those areas where the ground has been cut away and then had artificial ground deposited: the backfilled gypsum workings around Gotham [e.g. 5366 2916] are the main example of this category. Worked and Made ground carries the same potential hazard to development as Made Ground.

*Landscaped Ground* encompasses areas where the original surface has been extensively remodelled, but where it is impractical or impossible to separately delineate areas of cut and made ground. The principal examples in this area are recreational, industrial and archaeological sites.

*Disturbed Ground* corresponds to areas of ill-defined surface workings, usually for clay, in which ill-defined excavations are complexly associated with patches of Made Ground. The hazards posed by such areas will include the possibility of ground settlement above incompletely-filled excavations.

# 10. OTHER INFORMATION

## 10.1. Mineral Resources

There is currently no mineral extraction in the area covered by the map sheet.

### 10.1.1. Sand and gravel

Sand and gravel was formerly extracted from the outcrop of the Birstall Sand and Gravel in small pits to either side of the road at Woodside [5022 2717]. Diggings in Glaciofluvial Deposits were noted south-east of the track leading to Fox Hill Farm [5380 2701].

10.1.2. Clay

Clay pits, formerly used as sources of brick-clay and agricultural clay, are scattered throughout the Mercia Mudstone outcrop, generally within one kilometre of rural settlements. The most developed are located in the outcrop of the Cropwell Bishop Formation, on either side of Brickyard Lane [53333 2557; 5305 2505; 5327 2554], and close to the junction with Woodgate Road [5363 2531; 5375 2552]. Thrussington Till appears locally to have been used as a minor source of clay, giving rise to old workings to the east of St. Anne's Manor [5118 2520].

10.1.3. Limestone

The Barnstone Member limestone has been worked in a number of small quarries, rarely more than a few metres deep. The largest one lies just to the north of the area which it enters at Stonepit Wood [520 300]. The other quarries are also in the Barnstone Member where it caps the West Leake Hills. There are numerous shallow quarries in a belt about 300 m long to the west of Shiddock's Spinney [5385 2855] to [5352 2849], though some depressions around here may possibly be attributed to mining subsidence. Another cluster of shallow quarries lies to the north-west of Stone House [5373 2807] to [5339 2801]; Stone House itself is built of the local limestone. More quarries are present on the eastern end of the West Leake Hills. The largest excavation here [5465 2718] has been filled and returned to agriculture; two small quarries lie just to the north and north-east of it, one [5462 2733] is 2 m deep with no exposures, the other [5457 2724] is about 3 m deep with debris of laminated limestone.

10.1.4. Gypsum

Gypsum has a long history of exploitation in the area. The oldest mines for which abandonment plans exist were closed in the late 19th Century. The Winser and Coy Mine at the north end of the West Leake Hills [527 294] closed in 1896 (Plan No. 3592) and the adjacent Cartwright owned mine, also worked by Winser and Coy, [530 292] closed in 1899 (Plan No. 3978). Some of the old gypsum workings are fairly shallow, but the modern ones usually have a cover exceeding about 40 m. The only other mine, for which a publicly available plan is filed, is Weldon Mine (Plan No. 15255), the southern extent of which lies right on the northern boundary of the sheet [5204 3000]. Weldon Mine forms the southernmost part of the extensive workings that have taken place beneath Gotham Hill.

South of the Winser and Coy mines much of the area beneath the West Leake Hills was worked for gypsum between 1900 and 1990, but all mining here has now ceased. Because the rock dissolves at shallow depths, and because of the need to maintain a suitable thickness of cover rock, the mined area largely coincides with the higher ground composed of the Blue Anchor Formation or younger strata. Most of the high ground between Rushcliffe Lodge [548 276] and Hillside Farm [526294] has been undermined. A few areas outside of the crop of the Blue Anchor Formation have also been worked.

The extraction pattern of the mining has changed with time. The oldest workings went in to the hillside from near the outcrop and worked the partially dissolved gypsum beds. They followed the best stone and avoided the collapsed and marl-rich material which was left as pillars. The pattern of mining away from the main galleries is fairly random. In some places very little material was left as pillars and it is interesting that the only records of subsidence (see below) are where such workings have occurred. In addition to leaving small pillars, just before abandonment, some old mining companies robbed the good quality gypsum that formed the "roof ballstone". This further weakened the areas of extraction. All the modern workings for gypsum have been carried out on a regular, reticulate, well-engineered pattern of pillar and stall workings designed on careful rock mechanics principals.

Apart from the mine plans mentioned above no plans for these workings are on public file and reference to British Gypsum Ltd should be made for any details. Only a few farmsteads have been worked beneath. Most of the area is free of subsidence, but a subsidence depression about 80 m across was recorded next to the abandoned Cuckoo Bush Farm [5330 2877]. Another subsidence was reported to have occurred near to the former Kingston Mine Works [5240 2886]; these areas coincide with the ancient workings described above.

## 10.2. Water Supply

Surface drainage in the western and southern parts of the area is dominated by the north-draining River Soar and its main tributary, the Kingston Brook. In the north-east, Gotham Moor forms part of the River Trent catchment, with drainage to the north. As with most parts of the UK, the quantity and quality of surface waters has been greatly influenced by human activities; by analogy with the Loughborough region (Wilby, 1994; Figure 4.3) it is likely that summer flows on the River Soar are greatly augmented by artificial discharges principally made up of effluent from sewerage works. A small contribution also comes from mine water pumped from the former Kingston Mine [5247 2873] to prevent water ingress into other workings.

Information on the groundwater supplies of Leicestershire is given in Richardson (1931). For the present area the principal aquifer constitutes the permeable sandstones of the Bromsgrove Sandstone Formation (Sherwood Sandstone Group). This unit in turn underlies a minor aquifer, the Sneinton Formation, which was formerly known as 'Waterstones'. The Bromsgrove Sandstone aquifer, about 48 m thick, is confined by the Mercia Mudstone above and Carboniferous (Namurian) strata below. Depending on surface topography, its top will lie at depths of between 180 and 240 m to the north-east of the Normanton Hills Fault, but to the south-west of that structure it will be at lesser depths, possibly around 130 m. The Mercia Mudstone Group is generally impermeable, but the included sandstones can constitute minor aquifers, particularly those of the Cotgrave and Hollygate members. Zones of anomalous hydrological activity associated with gypsum dissolution may also occur, as discussed in Section 10.3.

The Sherwood Sandstone aquifer is on the whole fairly porous (Lovelock, 1972), and it has a high value for specific yield. Such data is sparse for the present area, but in the adjoining area to the west (Brandon and Carney, 1997) a yield of 7.72 l/s was obtained on test pumping of the Carters Soft Drinks Borehole: a transmissivity of 20 $m^2$/d was also obtained, indicating limited groundwater movement (Written communication, R. Marks, 1997). Further information from boreholes can be examined at the National Geological Records Centre of the BGS. A review of factors influencing water supply and quality of the similar Triassic aquifer in the Coalville district, to the south-west, is given in Worssam and Old (1988, p.130).

Strata below the Sherwood Sandstone Group are generally of uncertain correlation; however, at Ratcliffe on Soar, in the extreme north-west of the map sheet, a borehole (Figure 2) shows that they belong to the Namurian-age Edale Shale Group. Given the probable dip of these Carboniferous strata eastwards, towards the subcrop of the Westphalian strata forming the Vale of Belvoir Coalfield, sandstones belonging to the Millstone Grit Group may well subcrop below the Trias in the east.

### 10.3. Potential Geohazards Associated with Gypsiferous Strata

The natural dissolution of gypsum can be rapid if sufficient water flow is present through or over the rock (James, Cooper & Holliday, 1981). Where massive gypsum beds like the Tutbury Gypsum come to or near outcrop the result can be the formation of caves and the development of buried gypsum karst. In certain circumstances, with sufficient water flow caves and cavities can enlarge at a significant rate, become unstable and collapse (Cooper, 1986, 1995, Ryder & Cooper, 1993). Buried gypsum karst with some cavities has been described from the Tutbury Gypsum at Chellaston and Aston (Cooper, 1996 and references therein). Caves in the Tutbury Gypsum sequence have been described from Fauld Mine, about 40 km to the west of the area (Wynne, 1906), and cavities caused by gypsum dissolution were encountered along the route of the Derby Southern Bypass (Cooper, 1996).

The fact that gypsum can dissolve rapidly means that its presence should be treated with caution in any engineering works. In the area where the Tutbury Gypsum is present at shallow depth or comes to outcrop pinnacled gypsum karst, possibly with cavities may be predicted. The dissolution of nodules within the Newark Gypsum may also result in small cavities. The presence of thin fibrous gypsum veins, beds and nodules throughout much of the Mercia Mudstone Group can also cause problems. Gypsum veins, beds and nodules may dissolve producing cavities, or promoting water flow. The associated Mercia Mudstone may become brecciated, collapse and produce ground conditions of low bearing-strength. Such conditions were encountered in the ground adjacent to the Ratcliffe on Soar Power Station. Here the dissolution of gypsum layers was responsible for cavities up to 10 cm which formed the escape route for water leaking from the cooling ponds (Seedhouse and Sanders, 1993).

Development in areas underlain by gypsum calls for careful site investigation and conservative foundation design to avoid problems associated with gypsum dissolution and collapse. If cavities are detected and it can be proved that there is a negligible groundwater flow through them, grouting with sulphate-resistant grout may be feasible. If water flow through the cavities is suspected, it may be unwise to grout them since blocking the water flow may induce enhanced flow and accelerated gypsum dissolution around the sides of the grouted areas (Cooper, 1995). The chance of this happening can only be determined by careful site investigation and hydrogeological modelling.

Where gypsum is present in the bedrock, either as massive beds or as veins, it can be associated with sulphate-rich groundwater. This groundwater may remain local, or can migrate into adjacent drift deposits from which it may emanate as sulphate-rich spring water. Wherever sulphates and sulphate-rich groundwater are present they can harm concrete in contact with them. Precautions to prevent such damage must be considered (Forster et al., 1995). This situation applies to much of the Mercia Mudstone Group, especially the more gypsiferous sequences.

The Mercia Mudstone Group has a reputation for being deeply weathered, having a low bearing-strength and requiring careful site investigation (Chandler, 1969; Bacciarelli, 1993). Much of this lack of strength and weathering may be attributed to the dissolution of gypsum in the near-surface strata, possibly to a depth of 30 m (Elliot, 1961; Reeves, et al., 1993). In these rocks, caution should be exercised because engineering works, such as piling, may open channels for water ingress into the gypsiferous strata. If this happens, and there is a throughput of water, dissolution such as that detailed above for Ratcliffe on Soar Power Station (Seedhouse and Sanders, 1993) may occur.

In addition to dissolution problems the extent of undermining is a potential geological hazard in some parts of the area. Details of the mining and availability of information are given in section 10.1.4.

Over both mined and unmined areas underlain by gypsum, ingress of water from leaking services or from surface water disposal can have an exacerbating effect on both the natural dissolution of the gypsum and the collapse of the overlying strata. Care should be taken to ensure that soakaways are not constructed in these areas and that all surface water is piped away.

## 11. BOREHOLES

This section summarizes information about those boreholes mentioned in the text. The numbering system for these records commences with the map sheet number, followed by the number given to the borehole when it was archived (e.g. SK 52 NW/72). These records may be examined at the National Geological Records Centre of the BGS. In the following table the surface elevation of each borehole refers to Ordnance Datum (OD), and is given in metres above sea level.

| SK 52 NW/ | NGR | ELEV | NAME | SUMMARY LOG |
|---|---|---|---|---|
| 28 | 5246 2626 | 39.4 | - | Alluvium, Cropwell Bishop Fm. |
| 71 | 5009 2574 | 32.7 | - | Alluvium, Older Alluvium, Cropwell Bishop Fm. |
| 72 | 5081 2913 | 32.95 | Ratcliffe on Soar | Alluvium, Cropwell Bishop Fm., Edwalton Fm., Gunthorpe Fm., Radcliffe Fm., Sneinton Fm., Bromsgrove Sandstone Fm., Moira Fm., Edale Shale Gp., Widmerpool Fm., Long Eaton Gp. |
| 95 | 5005 2937 | 34.9 | A453(T) | Made Ground, Cropwell Bishop Fm. |

## 12. OTHER UNPUBLISHED SOURCES OF INFORMATION

This section presents in tabulated form the principal items of information used to compile this report and accompanying 1:10 000 scale map. Much of this information is available to public examination by application to the National Geological Records Centre of the BGS.

| ITEM | ORIGIN | DETAILS |
|---|---|---|
| Field slips: L10NE, DY56SE | C Fox-Strangways | 1:10 560; c. 1892-95 |
| Field slips: N50NW | R L Sherlock | 1:10 560; 1906 |
| Borehole records Nos. 1-99 | NGRC | Various dates; inc. site investigations |
| Aerial photographs | NRSC, Barwell | 1:10 000, colour, 1991 |
| Mine abandonment plans | British Gypsum | Various scales and dates |

## 13. ACKNOWLEDGEMENTS

The writers are most grateful to British Gypsum Ltd, East Leake, for allowing access to plans of former underground gypsum mines located to the north-west of East Leake. The conclusions and opinions expressed in this report, however, are those of the writers only.

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