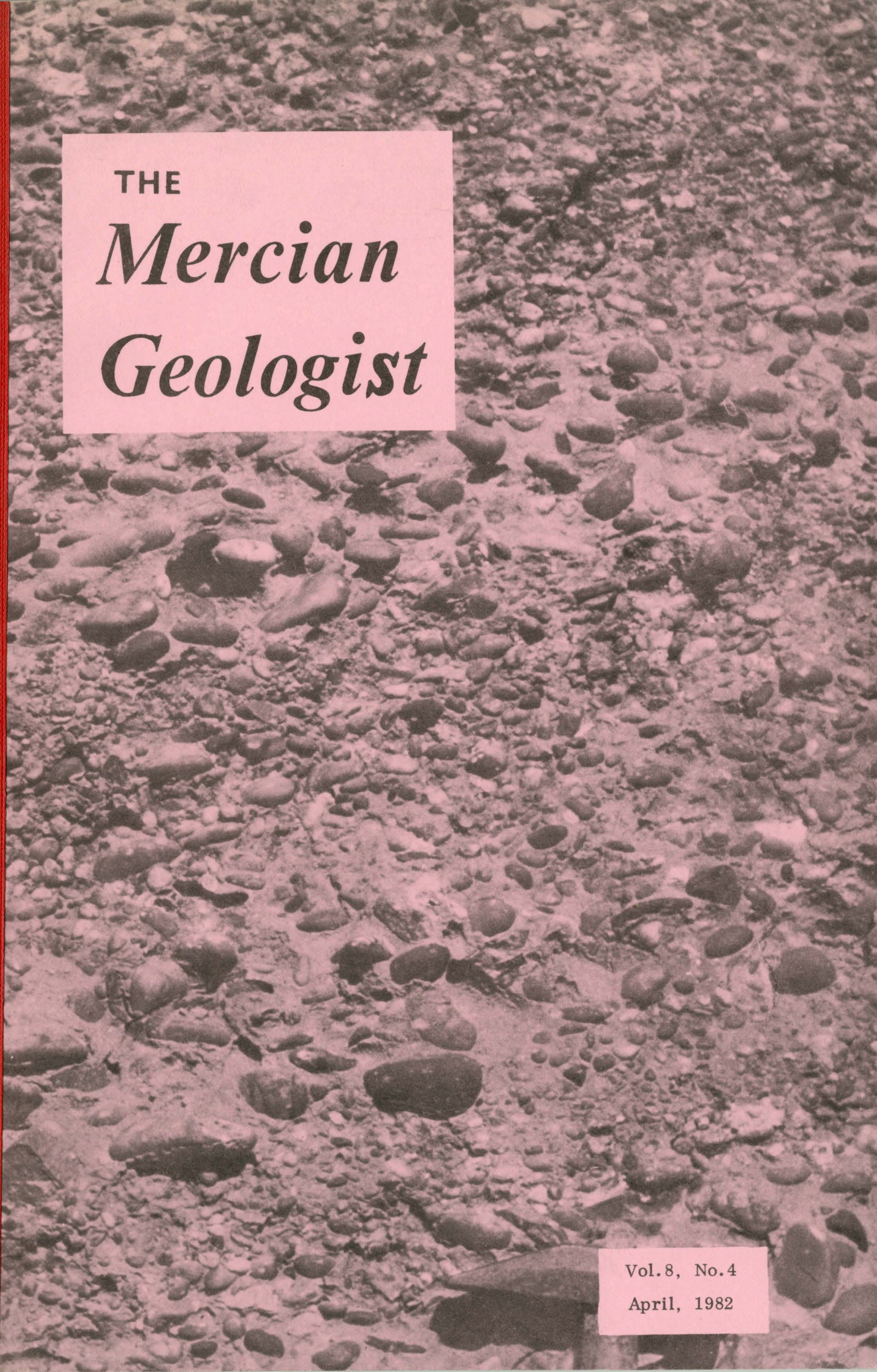
# THE *Mercian Geologist*



Vol. 8, No. 4
April, 1982

EAST MIDLANDS GEOLOGICAL SOCIETY

# THE MERCIAN GEOLOGIST

Editor:

F. M. Taylor.

Volume 8

Number 4

April 1982

CONTENTS




Mercian Geologist, vol.8, no.4,
1982, pp.241-323, plates 8-11.

# THE EAST MIDLANDS GEOLOGICAL SOCIETY

## Council 1981/82




Address for Correspondence,

General information, membership details:

The Secretary,
East Midlands Geological Society,
311 Mansfield Road,
Redhill,
Arnold,
Nottingham

Tel. No. (0602) 267442





ISSN 0025 990X

Printed by the Nottingham University Press.


Front Cover: Pebble beds of the Sherwood Sandstone Formation, Staffordshire-Derbyshire border. Photograph from colour slide, by D. Jones.

# SEDIMENTOLOGY, ENGINEERING PROPERTIES AND EXPLOITATION OF THE PEBBLE BEDS IN THE SHERWOOD SANDSTONE GROUP (?LOWER TRIAS) OF NORTH STAFFORDSHIRE, WITH PARTICULAR REFERENCE TO HIGHWAY SCHEMES

by

David S. Buist and David B. Thompson

## Summary

The geology of north Staffordshire is reviewed and the relationships of pebble beds in the Sherwood Sandstone Group to the overall succession and structure of the region are established. The problems of constructing highways over pebble bed outcrops are considered. Sedimentological studies show that these rocks belong to four facies, two kinds of pebble conglomerate or gravel, varying types of sandstone, and mudstone. All the facies are referred to parts of a former braided river environment. Data from maps, memoirs and sedimentological analysis of the rocks at outcrop do not provide a satisfactory basis for the engineer to plan the construction of cuttings and embankments in the pebble beds and further local site investigations are necessary. Traditional methods of sub-soil survey are reviewed and criticised and two other techniques, the excavation of trial trenches and down-the-hole photography are recommended. The behaviour of the materials of the pebble beds in relation to the planning and construction of cuttings and side slopes is discussed, together with comments on the most suitable methods of their exploitation in highway construction.

## Introduction

The purpose of this paper is to discuss problems of highway construction over pebble bed outcrops of the Sherwood Sandstone Group in the light of experience gained during the building of the M6 Motorway in the Trentham area of north Staffordshire (1958-1962). The problems relate to sedimentology and stratigraphy on the one hand and engineering geology on the other. The width of expertise needed to tackle these matters successfully proves to be wider than that possessed by specialists in either subject who experience difficulty in communication because of the conceptual frameworks and jargon used in each sub-discipline. It is equally difficult for a non-specialist, albeit with some geological knowledge, to attune to the proper consideration of the issues involved. This account, therefore, has been written with these points in mind and in draft form at least has proved to be acceptable to representatives of each of these three groups of interested persons. It is hoped that the paper will assist highway engineers in the future when dealing with this porous and relatively unconsolidated material.

Mercian Geologist, vol. 8, no. 4, 1982
pp. 241-268, 8 text-figs., plates 8-11, cover.

The problems which are highlighted in this communication are associated first of all with the degree of adequacy and suitability of the information available from published geological maps and memoirs, and even modern sedimentological analysis of rocks, in north Staffordshire.

Secondly there are difficulties of planning appropriate site investigations of both a geological and engineering nature. Geological studies on existing outcrops along a projected route are often meagre and better exposures in adjacent areas, though useful, cannot always predict, even on a statistical basis, the nature and behaviour of materials a short distance away from the site. Traditional techniques of 'site' investigation ('shelling', auguring, chiselling, rotary 'open hole' and 'lined' drilling, standard penetration test (SPT) blow counts, etc) prove to be inadequate or simply inappropriate and are certainly very expensive in relation to the information gained.

Thirdly, there is the uncertainty concerning the nature and behaviour of *in situ* materials in relation to the planning and construction of cuttings and embankments. Points for discussion include the suitability of pebble beds as a road foundation, the suitability of pebble bed materials excavated on-site to form a sub-base or road-base and the provision of safe side-slopes in these deposits.

Outcrops of pebble beds of the Sherwood Sandstone Group throughout the Midlands are readily recognised by their distinctive gravelly soil and topographical features which include rounded hillocks and scarps separated by rounded valley slopes. Vegetation is typically that associated with acid soils, the reclaimed ground being colonised by heather, gorse and silver birch and forested ground by conifers ringed by bracken.

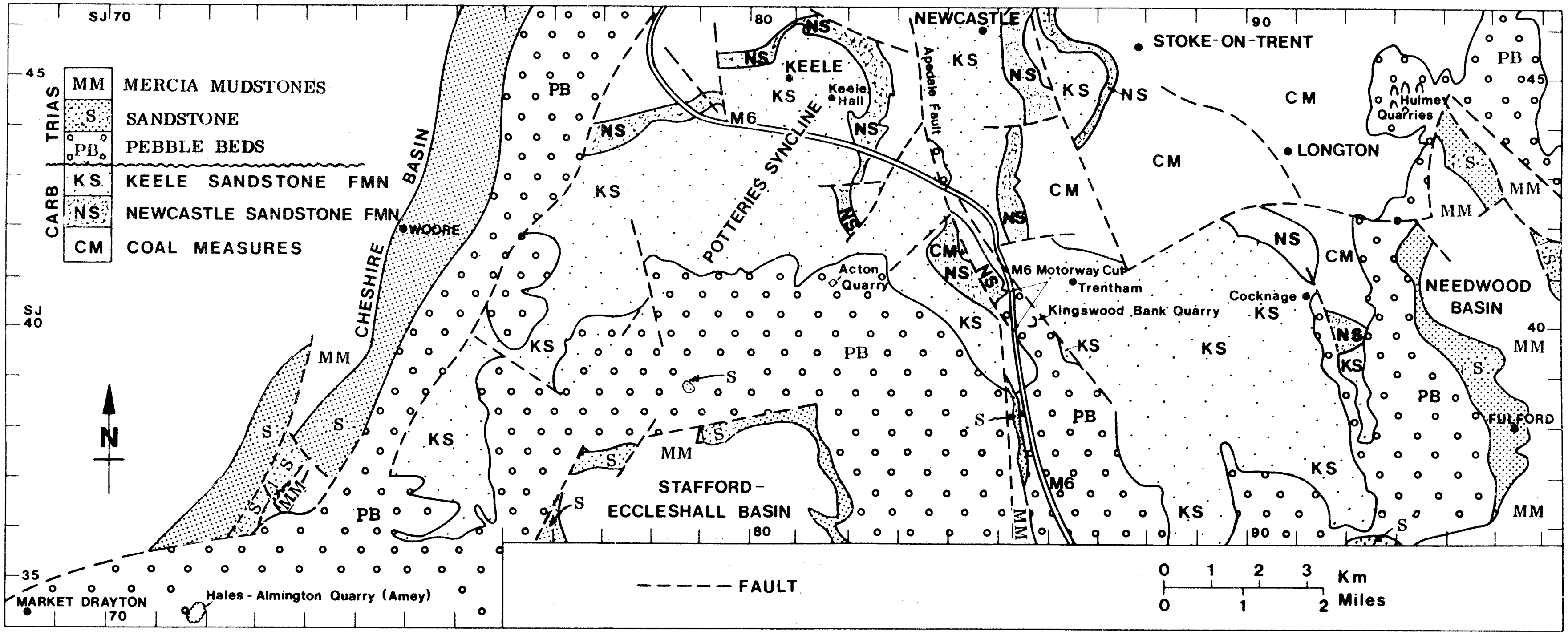
In the present area, the rocks outcrop at the northern ends of the Stafford-Eccleshall and Needwood Basins (text-fig. 1) in a region which was severely faulted during the Permian and in post-Triassic times. In the Trentham area, the M6 Motorway was constructed to take advantage of a natural north-south valley, the erosion of which was related to the presence of a splay of the Apedale Fault and outcrop of softer sandstones in the upper part of the Sherwood Sandstone Group pebble beds (text-fig. 1).

The construction of the section of the M6 through Kingswood Bank (text-fig. 2) in the 1960s provided the engineer with valuable experience relating to the problem associated with pebble beds. For the geologist, the roadworks gave access to a more complete succession than hitherto and the enlargement of local quarries provided the opportunity of making facies analyses. One of the present authors was able to supplement earlier studies (Thompson, 1970) and eventually these embraced an area from the Hales-Almington quarries in the west, through those at Acton, Kingswood Bank and Hulme (text-fig. 1) to Cheadle in the east.

During the preparation of this paper the stratigraphy of the Triassic rocks of the area was being revised by a committee of the Geological Society of London (Warrington *et al.*, 1980; table 1). Whilst the authors welcome this general revision in principle, the application of its recommendations to the writing of the present paper is most difficult. Whereas the outcrop of the Sherwood Sandstone Group is continuous from west to east and the formations/members to be named are not in dispute (table 1, column B), the fact that the committee has chosen to draw a boundary between two of its regions (cols. 10 and 11 in Warrington *et al.*, 1980, their text-fig. 2) halfway across the present area would require the authors to use different names for rock formations which are contiguous and of similar character; indeed the same rock sequence is divided into two formations in the west (the Chester Pebble Beds and the Wilmslow Sandstone) which are the lateral equivalent of one formation in the east (the Cannock Chase Formation) in which there is an un-named conglomerate member. The present authors believe that to try to use the new formation names as they now stand would be confusing and unhelpful in a paper of this nature and they resist the temptation to attempt a stratigraphical revision. The only new name of a rock unit introduced here is that of the Trentham Conglomerate Bed. The former 'Bunter' Pebble Beds are referred to informally throughout as pebble beds.

Table 1: Stratigraphical nomenclature of Triassic rocks from Market Drayton to Cheadle

| A. Traditional geological survey nomenclature 1850–1980 | B. Stratigraphic units requiring definition across present outcrop of study area | C. New nomenclature in north-central Staffordshire 1980– Stages | Groups | Warrington *et al.*, 1980, Fig. 2 Area 10. Table 4, Column 10 — West: Cheshire Basin; Hales-Almington-Lordsley-Maer-Acton-Trentham | | Warrington *et al.*, 1980, Fig. 2 Area 11. Table 4, Column 11 — Stafford-Eccleshall Basin; East: Needwood Basin; Hulme-Cheadle | |
|---|---|---|---|---|---|---|---|
| $f^6$ Lower Keuper Marl | Silty mudstones | ? Anisian, etc. | Mercia Mudstone Group | un-named mudstone formation | no members recognised | un-named sandstone formation | no members recognised |
| $f^5$ Keuper Waterstones | Interbedded sandstone and siltstone formation | | | Tarporley Siltstone Formation | | | |
| $f^4$ Lower Keuper Sandstone | Pebbly sandstone formation | | | Helsby Sandstone Formation | | | |
| ?Hardegsen | disconformity | | | ? Hardegsen | | disconformity ? | |
| $f^3$ Bunter Upper Mottled Sandstone | Medium-fine argillaceous sandstone formation | ? Scythian | Sherwood Sandstone Group | Wilmslow Sandstone Formation | no members recognised | Cannock Chase Formation | b un-named sandstone member |
| $f^2$ Bunter Pebble Beds | Pebble bed formation<br>c Pebbly sandstone mbr.<br>b Conglomerate member<br>a Pebbly sandstone mbr. | | | Chester Pebble Beds Fm. | | | a un-named conglomerate member |
| ? unconformity | | | | ? | | Pronounced relief on unconformity | |
| $f^1$ Lower Mottled Sandstone | Mottled sandstone (in west) | | ? | Kinnerton Sandstone Formation f | | | |




Text-fig. 1: Geological map showing the M6 route through north Staffordshire

## Problems with Geological Information

### Studies prior to 1971

Geological mapping of the north Staffordshire area was carried out by the Geological Survey of England and Wales on the one-inch scale by Smyth & Hull between 1852 and 1864, sheets 72NW, 72NE. The area was resurveyed on the six-inch scale by Gibson, Wedd & Barrow (1898-1901) in order to facilitate the publication of the New Series one-inch sheets 123 (solid and drift: 1902), part of sheet 124 (the Cheadle Coalfield: 1903), and 35 quarter sheets of the six-inch county series (1904). The far west of the area was resurveyed (sheet 122) in the 1920s, and parts of the Permo-Triassic rocks were included in a "wartime" revision by Cope (1944-7) which led to the publication of the provisional edition of six maps in 25 $km^2$ sheets (e.g. SJ 84SW, 84SE). The area was re-mapped on the six-inch scale in the 1960s by Boulton, Evans, Wilson and others of the Institute of Geological Sciences; however, no new maps have yet been published. The outcrop of the pebble beds to the east of the study area, forming part of the Ashbourne sheet, is at present being revised by the Institute of Geological Sciences.

For outline planning of routes of highways, one inch and six-inch geological maps are necessary, but in north Staffordshire these sometimes lack information provided in adjacent areas. For example, the separation of the lower gravelly pebble beds from the succeeding non-pebbly finer-grained sandstones formerly known elsewhere as the Upper Mottled Sandstone, may not be shown. For detailed planning, the six-inch maps are essential, but these prove inadequate, because the kind of detail set down in the outcrop areas of the Coal Measures is not attempted for those of the Barren Red Measures or for the Permo-Triassic rocks, where only information spot-sampled from small outcrops is recorded. Attempts to make geological maps upon which slightly greater facies detail is depicted within the Permo-Trias have been made by Boulton & Charsley (personal communications).

Memoirs which cover the Permo-Trias (Smyth, 1862; Hull, 1869; Gibson, 1905; Gibson & Wedd, 1905; Gibson, 1925) have been generally helpful in understanding the geology in a broad sense, but there is no modern memoir which gives a generalised succession, detailed local successions located by grid references, or a facies analysis which would assist an engineering geologist or highway engineer. In this respect, the treatment of the Permo-Triassic rocks in memoirs, even recent ones, has lagged far behind those describing the Coal Measures or Millstone Grit Groups.

From maps and memoirs, the following general geological picture has emerged. The pebble beds of the Sherwood Sandstone Group lie unconformably on the productive and unproductive Newcastle Sandstone and Keele Sandstone Formations. At their base the pebble beds are incoherent and sandy with few pebbles, but coarsen upwards to form a main mass of gravel and conglomerate which may be thicker near Cocknage (grid reference SJ 9140) than in the extreme west or east (Gibson, 1905, pp.140, 142, 269-72). In north Staffordshire, there is little hint at the base of the pebble beds of the presence of the sandy fine-grained Lower Mottled Sandstone (e.g. Bridgnorth Sandstone Formation, typical of west Staffordshire and east Shropshire). At the top of the pebble beds the conglomerates give way to more sandy beds (Wilmslow Sandstone Formation) which, in the west, on sheet 122 and on Hull's older maps, are designated Upper Mottled Sandstones (table 1, column A).

The early memoirs provided the first attempts at environmental interpretation. Gibson & Wedd (1905, their text-fig. 12) suggested that the pebble beds were laid down in a steep-sided ancient valley, the western slopes of which may have been influenced by the position of the Apedale Faults. The origin of the pebble beds was ascribed to "rapid irregular transportation, such as would result from occasional cloudbursts, letting loose sudden rushes of water and thereby causing floods" (Gibson & Wedd in Gibson, 1905, p.139), "the component sand grains betraying their desert wind-blown origin in the almost complete roundness of even the smallest grains" (*ibid*, p.140). The discovery of fossil waterfleas at Walsall (Cantrill, 1913), and later at Acton (SJ 8176 4119) (Wilson, 1962, p.43), was followed by the finding of reptilean footprints found in a bore-hole core at Sugarbrook, Worcestershire (Wills & Sarjeant, 1970), and these confirmed the suggestion of a continental environment. Accounts written by Molyneux (1861, 1867, 1876), Bonney (1880, 1900), Blaikie (1887) and indirectly by Wills (1948, 1951, 1956, 1970, 1976) and Campbell-Smith (1963) dealth mainly with the composition of the pebbles and the derived fossils (see also Gibson, 1905, p.143), and were useful in identifying source areas as far distant as the south Midlands and the south-west of England.

Wills set down an outline palaeogeography (1956, his text-fig. 17) which was supported generally by isotopic age dating of micas found further north in the Cheshire Basin (Fitch *et al.*, 1966). Thompson (1970) wrote a preliminary notice of the recognition of distinct pebbly sand and sandy facies around Acton and Trentham, together with evidence of palaeocurrents from the south and envisaged deposition from low-sinuosity rivers. Wills (1970) subdivided the pebble beds of the Midlands into macrocyclothems, which he called miocylothems, each made up of many microcyclothems. He interpreted macrocyclothems in terms of gravelly microcyclothems, deposited by a succession of floods, each gravelly microcyclothem being succeeded by more sandy and argillaceous microcyclothems deposited during periods of drought in a semi-arid to desert environment.

Studies after 1971

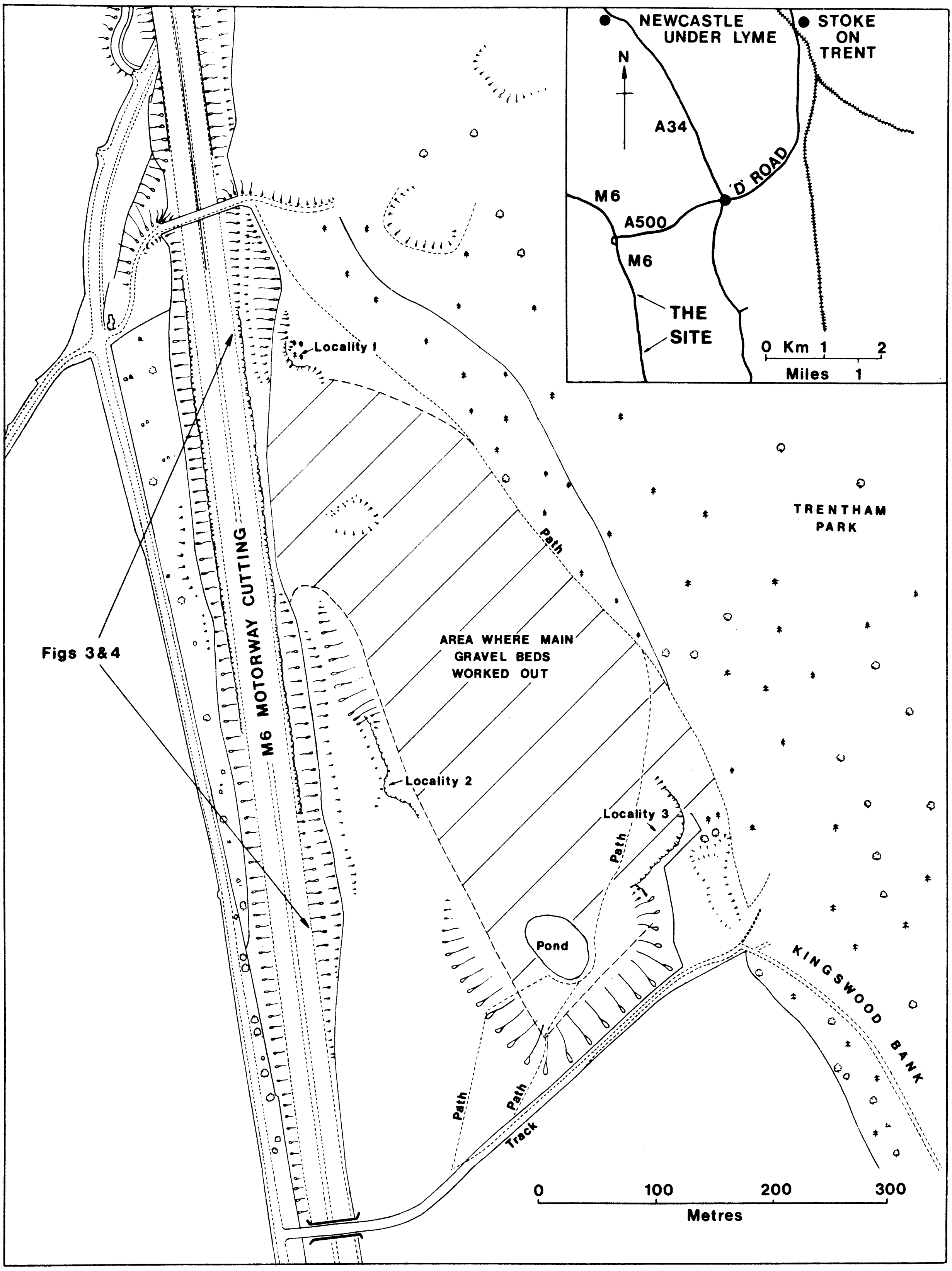
Geotectonic setting. Recently the geotectonic context of the origin of the basins in which the pebble beds were deposited has become clearer (McLean, 1978; Ziegler, 1981). The Cheshire and Worcester grabens originated from the collapse of the northern foreland of the Variscides sometime after the final aggregation of the Pangean supercontinent (Robinson, 1971). Initially narrow in the late Carboniferous or early Permian (cf. Wills, 1956, his text-fig. 14), the basins widened (*Ibid.*, his text-fig. 15) and were extensively filled with sediment as high eustatic sea levels developed in the late Permian (Vail, *et al.*, 1977). Thick aeolian and minor alluvial fan sedimentation was followed by an incursion of the Bakevellia Sea into north Cheshire from the north northwest (cf. Wills, 1956, his text-fig. 16; Pattison, Smith & Warrington, 1973). At approximately the beginning of the Triassic period there was intensified rifting which extended and augmented the number of basins and the area of deposition. The Stafford and Needwood basins arose and the Cheshire and Worcester grabens were extended. These events were accompanied by a temporary eustatic lowering of sea level (Vail ***et al.***, 1977) and ushered in a change of sedimentary regime. Sandy and pebbly continental deposits succeeded the Zechstein marine carbonates. The pebble beds of the Sherwood Sandstone Group spread unconformably across the very varied relief of the marginal horsts and into the sagging basins (cf. Wills, 1956; his text-fig. 16) wherein sedimentation probably kept pace with subsidence. This change of regime was succeeded by a general return to rising sea levels and the fining upwards of sedimentation from the mid-Scythian onwards. As noted earlier, Wills (1970, 1976) claims climatic effects, variable aridity, as the cause for the gross sedimentary rhythms.

Sedimentological studies of the M6 road cutting and local quarries have been extended since 1971. In the Kingswood Bank area (text-fig. 2), the pebble beds dip to the southeast across the line of the motorway and the apparent dip exposes a considerable section, of which approximately 85 m was measured (text-figs. 3 & 4). The cutting was studied in some detail at road level by special permission of the Motorway Engineer and the Police, but severe restrictions of access and unpleasant environmental factors (noise, fumes, spray, flying pebbles) prevailed, and it is fortunate that comparable exposures were available on Kingswood Bank in the workings of the former Trentham Gravel Company, now restored to public use (text-fig. 2; localities 1, 2 and 3). The information from the cutting and the Bank was especially important in that it allowed a unique view of the succession and its vertical, and to some extent lateral, variability, and this permitted a small degree of statistical analysis.

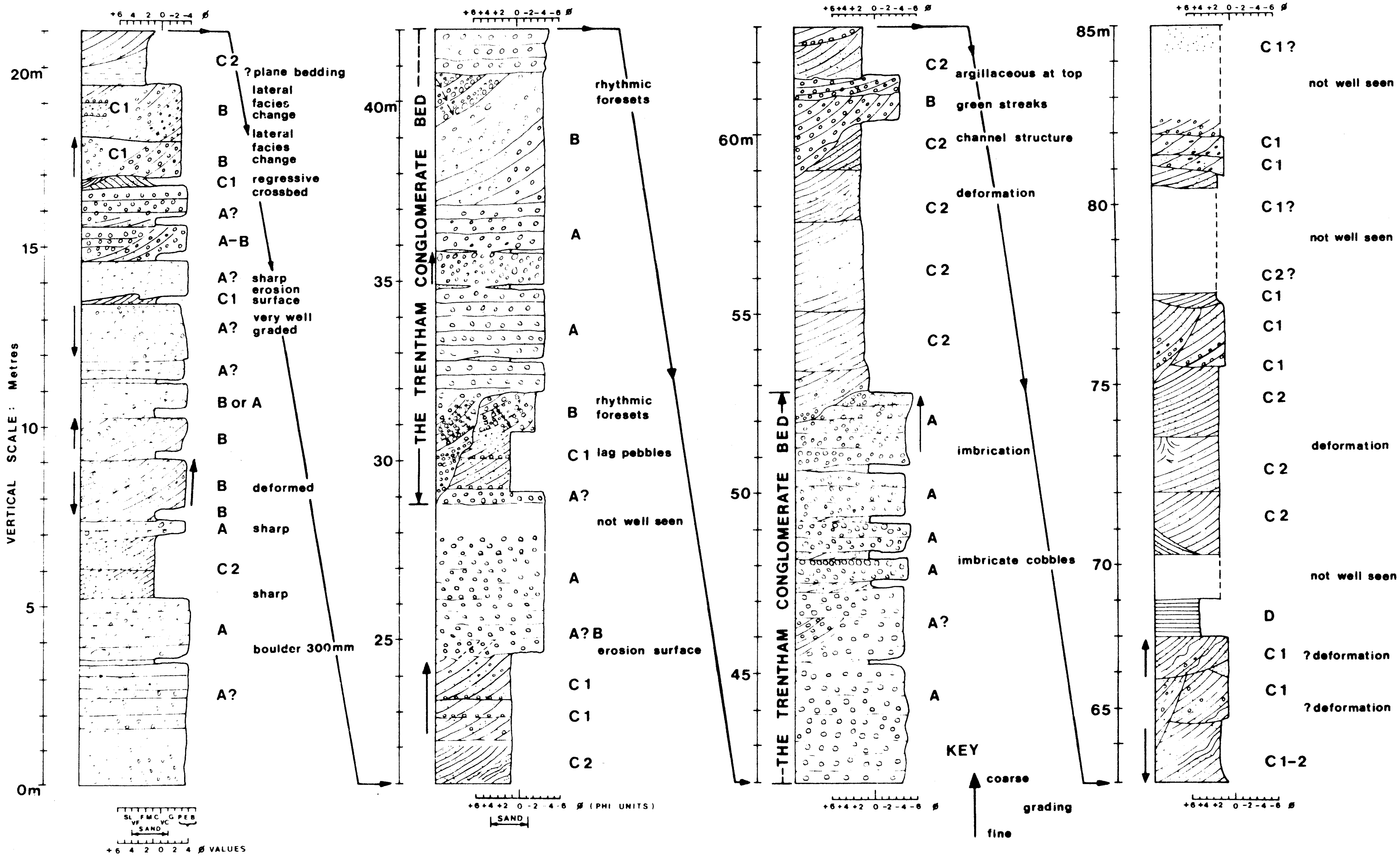
Outline description of the facies and petrography of the pebble beds in relation to highway schemes. Studies initiated after 1971 have demonstrated that the pebble beds consist of several major facies, four of which are specified here only in that detail which relates to their recognition and understanding by engineering geologists. Detailed sedimentological studies are currently in preparation by Steel & Thompson.

Facies A and B form the main gravel beds worked in any quarry, whilst the materials of Facies C1, C2 and D, although sometimes used, generally form an impediment to efficient working and have to be removed or backfilled. In the sedimentological account which follows, the grain-size terminology is that of the Udden-Wentworth scale.

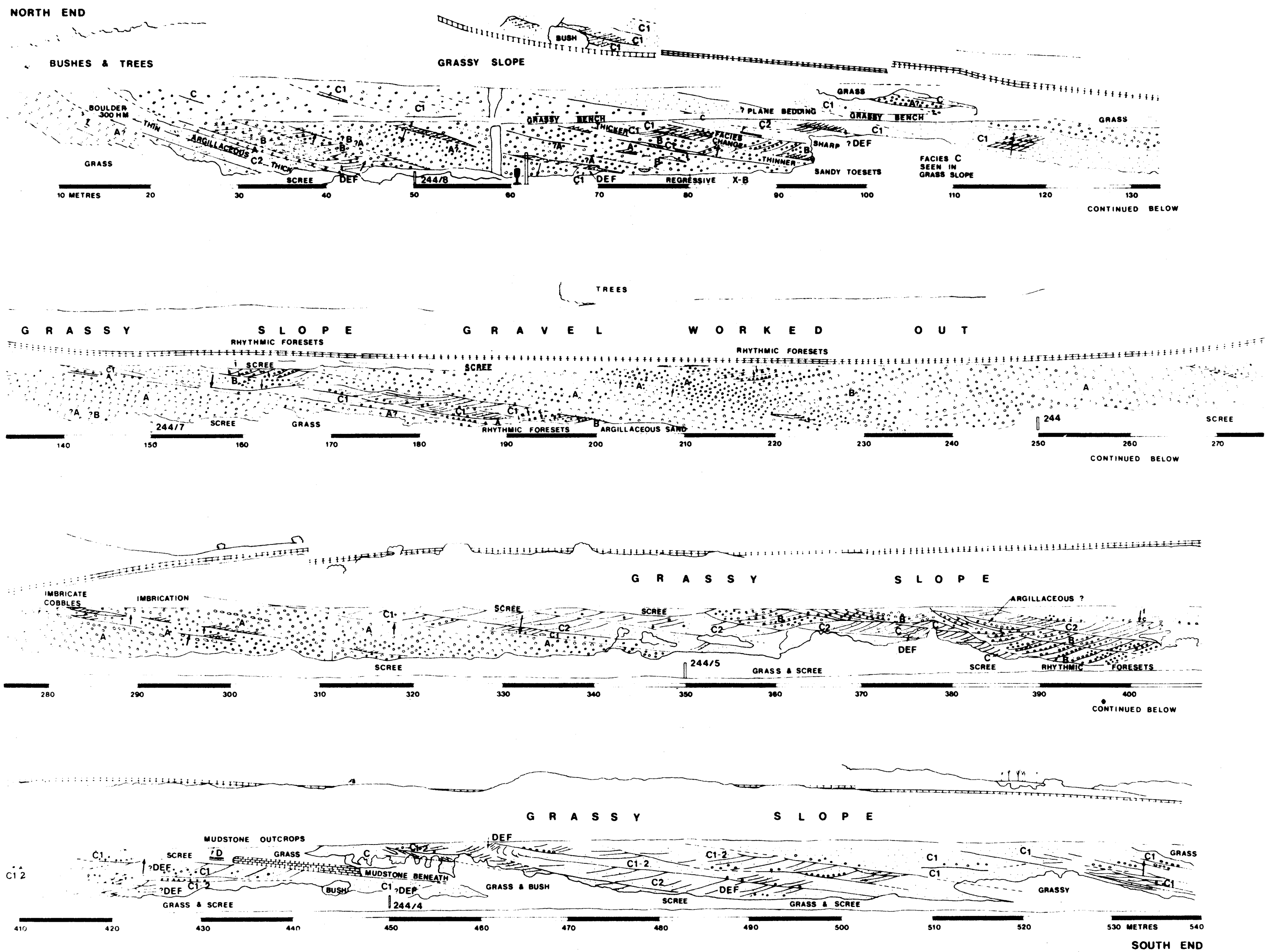
Facies A consists of flat-stratified clast-supported (often openwork) and matrix-supported pebbly conglomerate or gravel organised in units up to 10 m thick. The clasts range from boulders to fine sand, the grain size distribution being bimodal (text-fig. 5). One mode lies in the pebble grade, the other in the medium-fine sand grade. The largest clast observed is 600 mm in length and 1% of them exceed 100 mm. In the clast-supported part, the pebbles are usually in contact with each other, a few



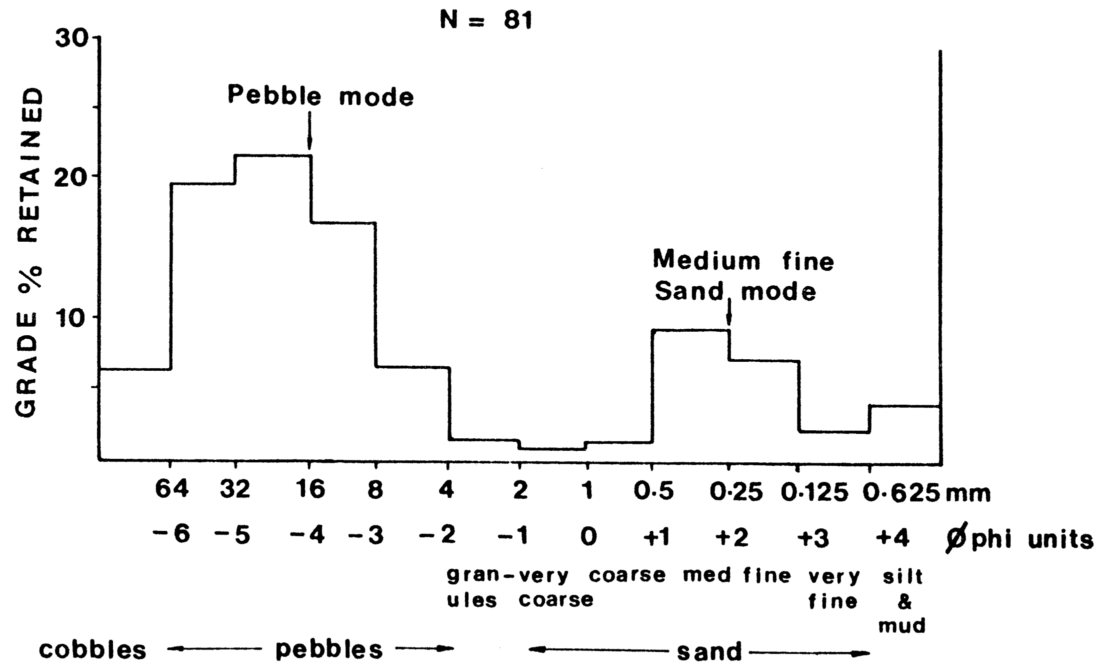

Text-fig. 2: The location of the M6 motorway cuttings and other localities near Kingswood Bank and Trentham Park.




Text-fig. 3: The geological succession on the eastern side of the M6 motorway cutting depicted in text-fig. 2. The succession should be read as a continuous one, starting at the base of the left hand column. The letters A, B, C1, C2, D refer to the facies types which are described in the text.




Text-fig. 4: An analysis of the sedimentary organisation of the eastern side of the M6 motorway cutting depicted in text-fig. 2. Drawn from a mosaic of photographs and subject to small distortions of scale.




Text-fig. 5: The grain size distribution of samples of conglomerate from the pebble beds in the area of Ordnance Survey Sheet SK 04 around Cheadle, Staffordshire (after Piper & Rogers, 1980; part of their text-fig. 4, p. 6).

cracked due to brittle fracture under superincumbent load or rapid build-up of tectonic stress. Most are pitted due to pressure solution (Barnes & Holroyd, 1897). This last factor contributes to the weak siliceous cement which is in places augmented by barite (Wedd, 1899). Pore space varies from about 40% in openwork gravel to 20% in matrix-filled clast supported beds (plate 8, fig. c). Imbrication, indicating a palaeocurrent from the south, is sometimes seen (plate 8, fig. a), but often the high degree of roundness (0.71) and sphericity (0.73) of clasts (Thompson, 1970, his table 3) may inhibit the formation of this structure. Close study of the pebbly horizons reveals many rhythmic couplets formed of large pebbles and sand matrix below, succeeded by better sorted finer pebbles, with or without sand matrix, above (plate 8, fig. b). Pebbles are mostly formed of very hard, often very smooth, vein quartz (approximately 30%) and non-porous fine-grained quartzite (about 50%), some of the latter bearing derived fossils from as far south as the English Channel. Rarer less smooth, softer, often wholly rotted pebbles include sandstones, tuffs, rhyolite, agate, cherts, limestones and porous orthoquartzites, the last three frequently containing derived fossils of Ordovician, Silurian and Carboniferous origins from the Midlands. Large 300 mm intraclasts of red mudstone are sometimes found. Thin lenses of medium sand up to 250 mm thick and 10 m in length, often cross-bedded, are interbedded with the gravel.

Several features which conspire to reduce the competence of this facies, make it a gravel rather than a conglomerate, and enable it to be worked by heavy machines such as the 38 RB (Ruston Bucyrus Ltd.) Face Shovel and the D8 Caterpillar Ltd. Crawler Dozer (bulldozer) rather than by blasting. These features are weak cement, cracked pebbles, high porosity, openwork lenses, smoothness and roundness of the pebbles, soft and rotted clasts, and intraclasts. As excavated, the material will not in general form a vertical face unless protected above by Facies C1, but will degrade slowly, the angle of its free face apparently stabilising at approximately 65° in the case of Trentham M6 cutting and the base of the face being carpeted by a widening scree, the slope of which is of the order of 30° (plate 11, fig. a; plate 11, fig. b).

Facies B consists of cross-bedded gravel or conglomerate (plate 9, fig. a) sets or cosets being up to 10 m thick, maximum 100 m long. The material has features akin to those of Facies A; comparable, but finer, grain-size distribution, similar shape and roundness indices, pitting, cracking, cement, pore-space and petrography. In addition, the foresets are often composed of repeated rhythms of large pebbles and medium sand matrix at the base, smaller pebbles with or without sand above, (plate 9, fig. b) followed in some cases by equally thick foresets of medium sand. The lower parts of cross-beds are sometimes composed of wedges of sand about 300 mm thick which may on occasions extend the whole height of the foreset. Measurements of cross-bedding suggest a palaeocurrent directed broadly from south to north (Steel & Thompson in preparation). The beds are easily worked by heavy machinery. Indeed, theoretically, the foresets should be more easily worked than in the case of beds in Facies A, for the processes of grainfall and avalanching which lead to their formation also gives rise to loose packing.

Details of how the petrography of these two gravel-conglomerate facies relate to properties of materials which are of relevance to highway construction are given in table 2.

Facies C - sandstones. Two end-members, C1 and C2, can be usefully recognised, with every gradation in between.

Sub-facies C1 consists of cross-stratified pebbly sandstones organised into sets which form successions generally 2-3 m thick (plate 10, fig. a; plate 10, fig. b) but extending to 10 m or more in thickness. Some units are known to extend in distance for nearly 1 $km^2$. Sometimes, the beds die out rapidly laterally or are subject to channelling by currents which deposited gravel. The pebbles, though of similar type to those in Facies A and B, are smaller. The sandstone is medium to fine, sub-angular to rounded, moderately sorted, with little argillaceous matter, and has a firm siliceous cement. Lines of pebbles often lie at the base of the cross-bed sets and along the foresets. More infrequently, mica is associated with small changes in grain size and help to form foreset laminae and splitting planes. Very rarely, these beds are evenly laminated and bear micaceous surfaces with primary current lineation. In some places, very large 1.5 m by 0.5 m intraclasts of red shale or mudstone of Facies D are incorporated in the cross-beds and provide a considerable working hazard in that they readily detach themselves and fall. The rock is sufficiently firmly cemented to form a vertical face, even where it is partly unsupported due to the weathering of Facies A and B below. It is possible to work the face by heavy machinery if attention is paid to further undermining the coherent rocks by working the incoherent below them and by opening up planes of weakness along micaceous foresets or planes of lag pebbles. A few well-cemented beds have been known to resist a D8 bulldozer equipped with a ripper.

Sub-facies C2 consists of red-brown cross-stratified medium to very fine grained, often argillaceous and micaceous sandstones with few or no pebbles (plate 10, fig. b; plate 11, fig. a). Beds are of comparable thickness or extent to those of Facies C1. Sometimes the cross-bedded units are deformed and the rock rendered structureless and more homogeneous. The clay minerals and the mica reduce the porosity and permeability, especially where the facies forms the bottomsets of cross-bedded units. These characteristics are related to the establishment of perched water tables, which can often be recognised by changes in the vegetation. In a free-standing face, the strata may weather out after a few years and be the site of a deep recess which requires infilling if superincumbent beds are to remain stable. The sub-facies may be worked by heavy machinery in the same manner as that described for sub-facies C1. This sub-facies is further sub-divided and treated more fully in Steel & Thompson (in preparation).

Facies D comprises red mudstone, often misnamed 'marl', and thinly interbedded micaceous mudstone, shale, siltstone and fine to very fine argillaceous sandstone. The facies is never very thick, of the order of 1 m, or laterally extensive and its upper surface often shows erosional relationships with all other facies (plate 10, fig. a). Fossil waterfleas, *Euestheria* cf. *minuta* von Zeiten, have been found (Cantrill, 1913; Wilson, 1962, p.43). The rock is so impermeable that a perched water table is often present and so soft that immediate excavation and support is necessary in a highway cut (text-fig. 4).

Table 2: The petrography of gravel Facies A and B and the nature of groundwater in relation to properties of relevance to highway construction. PB = the pebble beds in the Sherwood Sandstone Group.

| Properties and Petrography | Implications for highway construction |
|---|---|
| 1. Grain-size distribution ('grading')<br>The grain-size distribution of Facies A and B shows only a small proportion of fine particles less than $\frac{1}{4}$mm (+2ø: medium-fine sand): mean approximately 14%, according to text-fig. 6. | Samples of materials from outcrop and boreholes have to be tested by sieving (British Standards). It is necessary to remove 'fines' (less than $\frac{1}{4}$mm), so that they form less then 5% of the aggregate. Material composed of a range of grain-sizes (-6 to 4ø), as in the PB (text-fig. 6): is very suitable for compaction into a sub-base and roadbase and for the manufacture of concrete, since excess of voids is not likely to present a problem. |
| 2. Surface textures of clasts and cementation | |
| (a) Smooth to very smooth pebbles common (wind-blasted, according to Wills). Pressure solution pits frequent: many clasts (particularly of vein quartz and quartzite) have small % pore-space within their mass or on their surface. Silicification is the dominant cementing process; hematisation also occurs (see (4) below). | (a) Smooth surfaces and hematite cement are not conducive to the formation of a good bond between the particles of the aggregate and the cement, but this is mitigated by the number of clasts in which the roughness is provided by pressure solution pits and a silicified, slightly porous surface. The lack of interior porosity of most clasts means that concrete made from PB is not subject to freeze-thaw fracture (Hartley, 1974). |
| (b) Clay minerals may coat particles both naturally and during the washing process. | (b) Weak bonds form between aggregate and cement unless clay is removed during washing and screening process. |

| | |
|---|---|
| **3. Mineral composition: presence of deleterious materials** | |
| (a) Material dominated by quartz and quartzite (both metaquartzite and orthoquartzite). | (a) Material conforms to specifications for road and bridge-works (Department of Transport 1976) in that it is dominated by chemically 'inert' clasts and has little deleterious material which may cause the problems cited below. |
| (b) Micas, illitic clay minerals, chlorites, rotted tuff (with montmorillonite) present in small % in Facies A, B and C: higher % in C2 and D. | (b) These minerals absorb water, expand and lead to failure of concrete, but this is not a problem in aggregates drawn from PB gravels of Facies A, B and C1 which have been well-washed. Deleterious material of Facies C2 and D should not be used for making concrete and is of less use for unconsolidated sub-base or roadbase. |
| (c) Agate, chert and rotted chert present in small %. | (c) The alkali content of cement reacts with opaline/chalcedonic silica, leading to gel formation and weakness of concrete, but this is not a problem in aggregates derived from PB. |
| (d) Shale and mudstone intraclasts form small % of gravel, but occasionally make an intraformational conglomerate. | (d) Intraclast mudstone blocks can pass into the screening and washing process, in which case the mudstones swell, become plastic, make contact with other clasts and coat them with clay, so making material unsaleable for the manufacture of concrete. |
| **4. Groundwaters in areas of outcrop** | |
| All groundwaters to a depth of at least 100 m are oxidising and undersaturated with respect to carbonates (Edmunds & Morgan-Jones, 1976), sulphates and other salts. | Few problems are to be expected with respect to the growth of deleterious salts from groundwater if PB gravels are used direct from outcrop to make concrete. Washing to remove the 'fines' will, in any case, dilute original groundwater salts. |

## PLATE CAPTIONS

### Plate 8

Fig. a Facies A. General view near top of Trentham Conglomerate Bed. Note flat bedding and imbrication indicating a palaeocurrent directed from south to north. The scale changes up the slope due to the camera angle; the uppermost conglomerate bed is 0.75 m thick. East side of M6 Motorway cutting, central section.

Fig. b Facies A. Matrix-supported conglomerate (at the top) and clast-supported conglomerate with matrix of medium sand (below). Acton Quarry: in the succession below the old weighbridge (SJ 817410).

Fig. c Facies A. Flat-bedded, largely clast-supported pebble conglomerate. Note the rhythmic couplets: clast- or matrix-supported units ($A_1$) below succeeded by finer clast-supported conglomerates $A_2$ above. The frameworks are either filled with medium sand or remain unfilled, hence the different porosities and permeabilities of the rocks, as mentioned in the text. Acton Quarry: in the succession below the old weighbridge (SJ 817410). Scale 1 m.

### Plate 9

Fig. a Facies B. A very large (c.7 m thick) crossbed set with spectacularly rhythmic foresets in conglomerate. This bed is succeeded upwards by flat-bedded medium sandstone (0.30 m), flat-bedded or lowly inclined gravel (c.2 m thick) filling shallow troughs, and at the top by pebbly sandstone (facies $C_1$). The geologist is 1.75 m tall.
Acton Quarry: southeast face of the pit worked between 1977 and 1981: SJ 820412.

Fig. b Facies B. Rhythmic couplets of matrix-supported and clast-supported pebble conglomerate developed on the foresets of the very large crossbed set depicted in Fig. A, above.

### Plate 10

Fig. a Facies $C_2$ at the base succeeded by facies $C_1$ and A. Note the yellow to pale-green reduced spots and stringers along certain foresets in the crossbed set (1.25 m thick at the left) in facies $C_2$. Acton Quarry: the uppermost part of marker bed Z, 200 m SW of the crushing and sorting plant; SJ 816410.

Fig. b Facies $C_1$, crossbedded pebbly sandstone, interbedded with an eroded and thinly preserved lens of lithofacies D, red shale. A lens of lithofacies A is developed at the top of the picture. Scale one metre. Acton Quarry, northern end 1973; SJ 818413.

### Plate 11

Fig. a Facies $C_2$, less pebbly argillaceous crossbedded medium sandstone, interbedded with facies A, flat bedded gravel, developed above basal erosion surfaces. Lithofacies B at the top of the picture is badly weathered and forms a loose scree slope. Note that the 65° slope of the original cutting has been modified by weathering, mass movement and erosion. The gravel scree at the base of the cut-face is grass covered; the embankment at the far left to the north is man-made and has a slope of c.35°. The hammer is 30 cm long. The northern end of the eastern side of the M6 motorway cutting looking north.

Fig. b View from the hard shoulder of the M6 in order to show the design of the present rock trap and the carpet of scree, largely grass covered, at angles up to 25° at the base of the cut-face which has stabilised at c.65°. Note the potentially lethal pebble on the hard shoulder on the wrong side of the rock trap and by the right of the tape measure. Tape measure 17 cms. diam. Central part of eastern side of the M6 motorway cutting looking north.

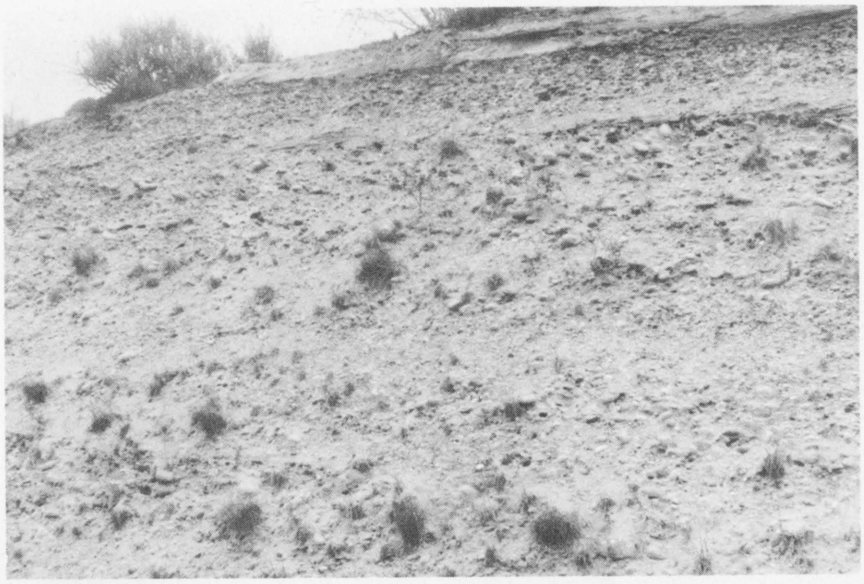


Fig. a

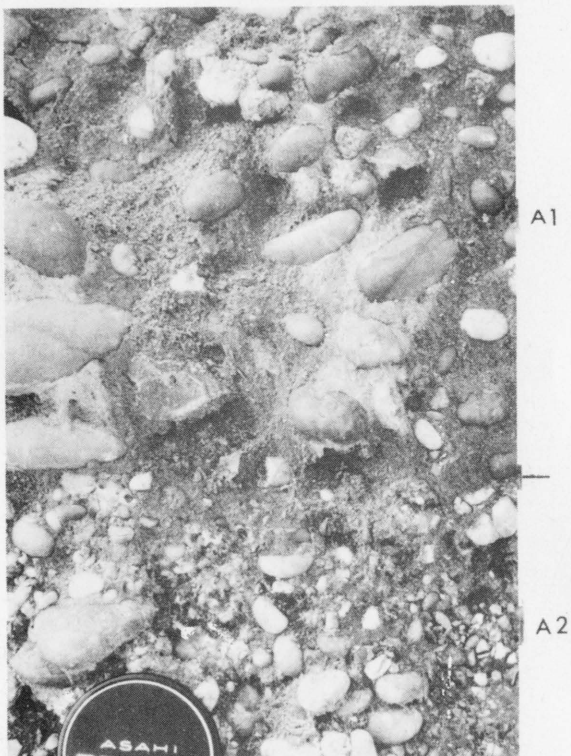



Fig. b

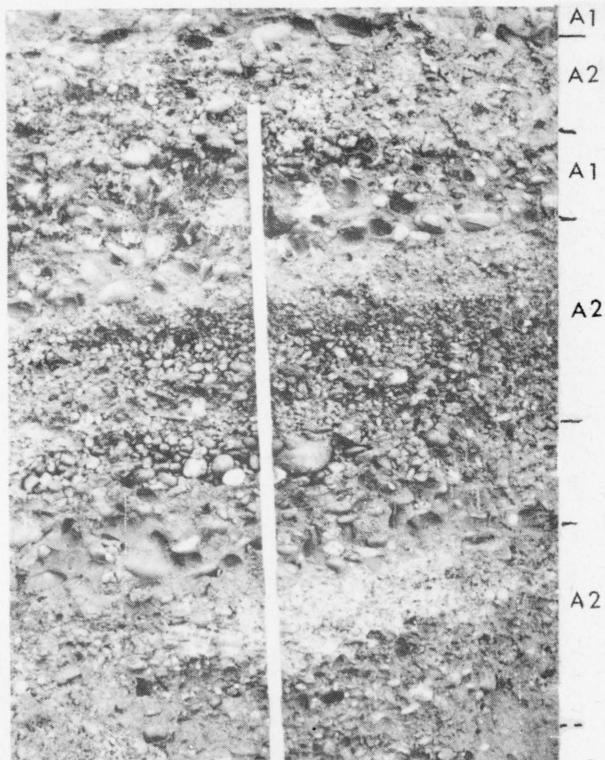



Fig. c

Buist & Thompson - N. Staffs. pebble beds, Sherwood Sandstone Group
See explanation p. 254.

Fig. a

Fig. b

Buist & Thompson N. Staffs. Pebble Beds, Sherwood Sandstone Group

See text and p. 254

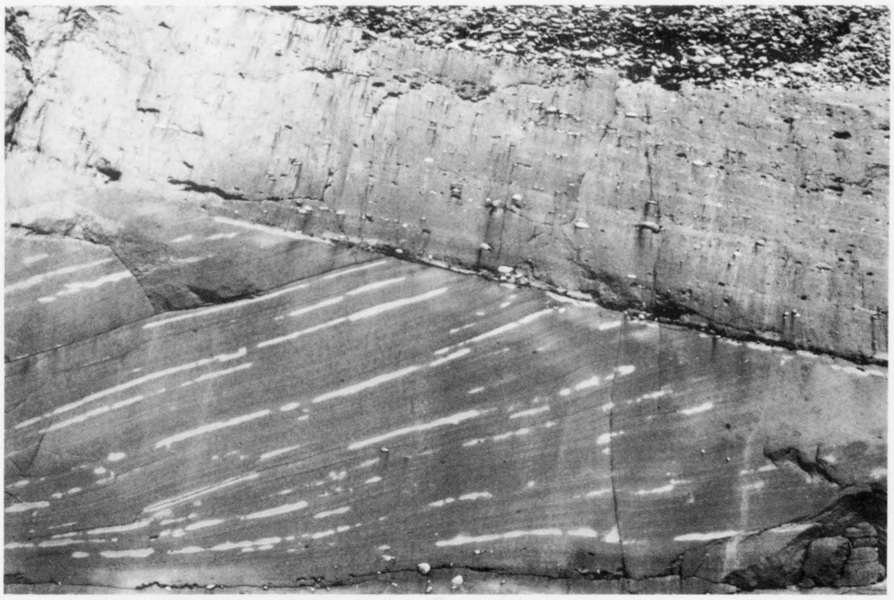


Fig. a


Fig. b

**Buist** & Thompson - N. Staffs. pebble beds, Sherwood Sandstone Group
See explanation p. 254.

**Fig. a**

**Fig. b**

Buist & Thompson - N. Staffs. pebble beds, Sherwood Sandstone Group

See explanation p. 254 and text.

Facies distribution in relation to the needs of the highway engineer:

Table 3 gives some idea of the proportions of facies which were present in the M6 cutting at Trentham, but attention is drawn to the gradational nature of the facies, especially C1-C2, the subjectivity of the division of the succession into three parts, and the arbitrary manner of the choice of the beginning and end points of the units. The difficulties of analysis caused by the channelling of one facies by another were resolved by assigning 50% of the thickness of any overlap to each of the two facies divisions when calculations were made.

Table 3: The incidence of Facies A, B, C1 and C2 and D recorded above a datum at the base of the pebble beds in the Trentham Motorway Cutting. The succession is divided into three arbitrary, but equal parts for the purposes of calculating the percentages of facies present at each horizon. The mean values are derived from averaging the results for the three successions.

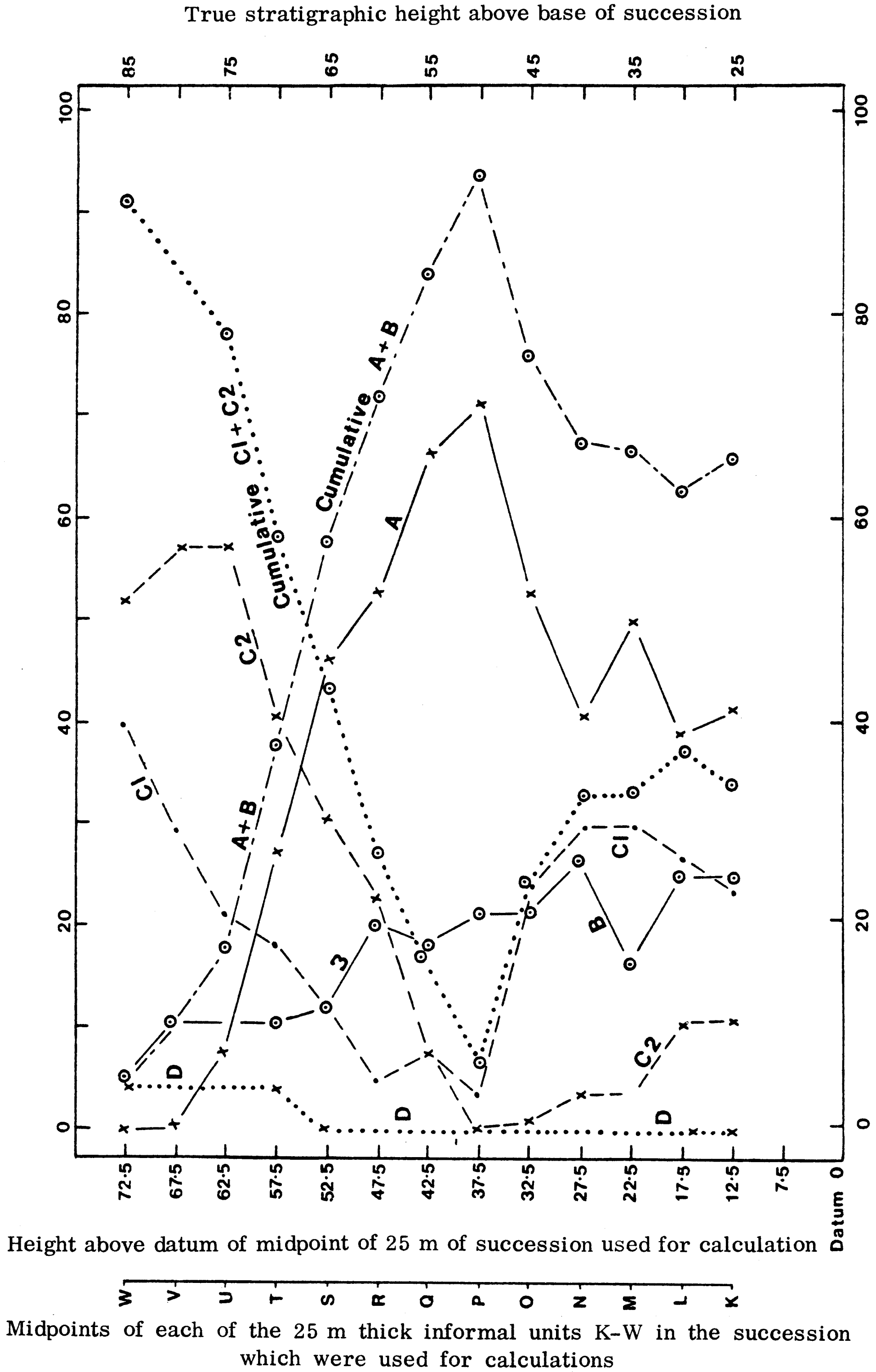
| Facies unit | A (%) | B (%) | C1 (%) | C2 (%) | D (%) | gravel and conglomerate A + B (%) | sandstone C1 + C2 (%) |
|---|---|---|---|---|---|---|---|
| Top of succession: 55-80 m above datum | 0.00 | 10.20 | 29.40 | 56.40 | 4.0 | 10.20 | 85.80 |
| Middle of succession: 30-55 m above datum | 66.40 | 18.00 | 7.60 | 8.00 | 0.00 | 84.40 | 15.60 |
| Base of succession: 5-30 m above datum | 37.80 | 25.00 | 26.60 | 10.60 | 0.00 | 62.80 | 37.20 |
| Mean for whole succession % | 34.73 | 17.73 | 21.20 | 24.87 | 1.33 | 52.47 | 46.07 |

In an attempt to give a picture which is less arbitrary and more pertinent to a highway engineer who is concerned with the mean chances of working certain percentages of these facies at any horizon above the base of the pebble beds, a moving average was calculated for 25 m thick successions, with a 20 m overlap between each division (text-fig. 6).

Inspection of text-figs. 3, 4 and 6 reveals the following:

1. The coarsening upwards of the lowest 50 m of the succession from Facies C1 at the base to Facies A and B at the top. The base of the succession is now covered by a grassy motorway embankment, but basal sandstones were formerly observed to outcrop there, and comparable sandy beds of Facies C1 can still be seen in the road cuttings near Whitmore Hall (SJ 810.412), Acton village (824.417) to the east of the Duke of Sutherland's monument in Trentham Park (871.388) and at Willfield Quarry near Hulme (926.453). In the basal and middle succession exposed in the cutting, Facies A and B comprise 63-84% of the whole (table 3).

2. A central part of the succession, from 29 m - 53 m above datum, which comprises the main gravel bed of the region, and is here designated as a new stratigraphical unit - the Trentham Conglomerate Bed (see text-fig. 3). The section is estimated to begin between 38 and 43 m above the base of the pebble beds but not quite coinciding with the middle of the succession as arbitrarily defined in table 3.




Text-fig. 6: The mean changes of distribution of facies type upwards in the Trentham motorway cutting. Each data point relates to the percentage of facies of that type present in a 25 m thick succession. In an attempt to be helpful to a highway engineer trying to predict the likelihood of the incidence of different facies types in a very variable succession, the results have been calculated as a moving average, each 25 m unit of succession (L-W) having a 20 m overlap with the unit in the succession below.

3. In the top 30 m the sediments become finer in grain-size with Facies C1 and C2 occupying more and more of the succession, from 20% at the base to 90% at the top, see text-fig. 3. This foreshadows the dominance of a pebble-less Facies C2 in the in the Upper Mottled Sandstone ( Wildmoor Sandstone Formation), former exposures of which were seen southwards of the present outcrops in the motorway cutting.

4. There is great vertical variability, which is typified both by fining and coarsening upwards of individual beds and facies groups and by sharp changes of facies, neither of which is as predictable or as easy to recognise as an engineer would like (Steel & Thompson, in preparation).

5. The great lateral variability is not only due to the channelling and filling relationship of one facies to another, but by individual facies showing gradational relationships (A-B, B-C1, C1-C2) at the same horizon. This is again a feature which has an unpredictable distribution.

6. There is a lack of evidence of predictable distributions of facies on a large scale such as suggested by Wills (1970, his text-figs. 1, 2 and 3). His miocyclothems I, II, III and IV were each stated to be between 20 and about 100 m thick, but they cannot be recognised objectively by the present authors.

Outline environmental interpretation of the facies of the pebble beds:

Sedimentary characters used to interpret the environment of the deposits include the abundance of gravel and pebbly sand, the dearth of argillaceous matter, the lateral and vertical variability of facies and the alternation of open and closed frameworks. There is a general lack of sedimentary organisation, an unpredictability of facies sequence, the extensive development of channelling, and the unidirectional palaeocurrent system with narrow variance in both gravel and sand (Steel & Thompson, in preparation). These characters suggest that the environment of deposition was that of low-sinuosity braided rivers.

Facies A is likely to relate to the layer by layer growth of sheets of pebbles on longitudinal and/or diagonal bars of low relief under very high flow energy, mainly at high flood. Great thicknesses of the facies may represent the superimposition of several bars on the same site (e.g. the middle of the succession in table 3).

Facies B relates to the development of foresets by avalanching at the tails of longitudinal, diagonal or transverse bars, perhaps under conditions of somewhat reduced sediment and water discharge (Hein & Walker, 1977), possibly on the tail of bar platforms (Bluck, 1976).

Facies C. Thick, widespread developments of this facies may relate to the growth of large transverse and tongue-shaped bars (Miall's sandy foreset bars, 1977, p.16), generated during flood stages and formed by the preservation of parts of sandwaves and dunes, the migration of which give rise to scour and fill structures, cross-bedding and lag pebbles. Thin units of this facies interbedded in gravel are likely to represent bar tail and bar lee deposits of longitudinal, diagonal and transverse gravel bars.

Facies D represents topstratum deposits settling from suspension on the margin of the riverplain, in abandoned channels, in the backwaters adjacent to the main channels or in the pools on the rippled top of arrested sandbars, as water discharge falls. These deposits are readily eroded when discharge again rises and flow resumes, or when channel switching takes place as the flood stage is reached; hence the limited appearance of blocks of mudstone incorporated as clasts in Facies A, B and C.

At the present day, on riverplains and alluvial fans, all these facies are being deposited somewhere in a braided river environment, at all but the highest and lowest discharges - hence at least one reason for the lateral variations of deposits at any one horizon (see Rust, 1979, his text-figs. 14 and 16). Variations of water discharge with time, and the shifting of the focus of energy input to and fro across the riverplain or fan will account for the rapid vertical variations of facies. The broader vertical trends in grain-size within the facies are exhibited by the coarsening-up at the base and the fining-up from the middle to the top over the whole region. This must relate to more general controls of total available energy and discharge, but do not equate readily with the four-fold cyclicity which Wills (1970) claimed to exist in the Midlands and be due to climatic causes.

In conclusion it must be confessed that despite all the geological information available, the foregoing analyses solve few of the practical problems of the highway engineer.

## Problems of site investigation in the pebble beds

Although general facies mapping, facies analysis, and sedimentological interpretation are extremely useful in recognising the deposits and understanding their engineering characteristics, and even in making some firm but broad predictions, they will be of limited use in coping with the problem of forecasting local details in a cutting say 0.5 km long and up to 20 m deep. The practice of the Institute of Geological Sciences Mineral Assessment Unit in drilling one borehole to a depth of 65 m every 4 $km^2$ (Piper & Rogers, 1980, p.7) is clearly inadequate for our purposes, as would be their close-sampling density of one hole per $km^2$ Hence a site investigation will be necessary in these beds, however competent the general geological advice may be.

Hitherto there have been no accounts of the engineering properties of site investigation techniques relating to the pebble beds or the Upper Mottled Sandstone (Wilmslow Sandstone Formation). General advice on the planning of site investigations for motorways is given by Wakeling (1972) and Francis & Tomlinson (1972), but this general advice is not specific and is inadequate for our purposes. Although a case history of exploration in north Staffordshire is given here, including examples of what would now be regarded as bad practice, the authors believe that the points which are made have a general applicability to the rock units under discussion wherever they outcrop in the Midlands generally.

In site investigations up to 1971, methods traditionally used on other rock formations were attempted; shelling, auguring, chiselling (by cable tool percussion rig); rotary 'open-hole' cased and cored drilling (rotary air flush). Standard penetration test (SPT) blow counts were carried out in all types of borehole.

Only shelling yielded samples useful to the highway engineer (Forshew, 1971; Slaney, 1974). The use of the shell with a casing resulted in jamming, as small pebbles and fragments wedged between the shell and casing. The casing tended to lock with the shell as the latter was withdrawn. This resulted in caving along the length of the uncased hole. At other times, the material around the casing tightened up, making it difficult to drive. In one instance it proved impossible to extract the casing on abandoning the hole, though admittedly this was exacerbated by misalignment of the former. Changes from 0.2 m to 0.25 m casing had little effect and the rate of drilling was often slow or at worst nil for long periods. The clay cutter tended to 'bounce' on the material and samples could not be picked up. Chiselling destroyed the matrix, pulverised the pebbles and was only used in the end to break out obstructions while shelling was proceeding. Shot drilling was used only at the largest diameter. Rotary drilling did no more than prove the material, giving no indication of change in packing density or any acceptable percentage of core recovery. Small diameter rotary open-hole drilling proved impractical in many places, as the sides of the boreholes tended to fall in and progress was negligible. Rotary core drilling often tended to cause loose pebbles to line the hole and removed the cutting edge after a few mm penetration. On the other hand, the suggestion of Forshew (1971) that a larger diameter rotary drilling technique be utilized proved to be more effective in later investigations. Drilling tends to be expensive for other reasons, not least because of the need for many closely-spaced holes in a formation of great vertical and lateral variability. For purposes of assessment of gravel resources, data from standard penetration test blow counts are known to be very difficult to interpret, but those in the pebble beds proved to be wholly misleading. It was entirely possible for the cone to hit and bounce off a large pebble at a horizon where the actual rock formation was of only medium or low strength. In continuing boreholes for this purpose, chiselling was limited to 1.5 m lengths since it was charged at an 'extra over' rate which was £12 per metre at 1976 prices but was still not as expensive as cored holes at £20 per metre. When this length was reached, the hole would either be abandoned or attempts made to continue with rotary coring. Because of the amount of chiselling needed to prove an area, difficulties arose over payment and boreholes were abandoned in places where ideally they should have been taken down to prove the thickness of the pebble beds below formation level in the cuttings. However, in beds with few pebbles, it is possible to use standard penetration test (SPT) results. Their relative simplicity, ease of operation, and cheapness means that they are appropriate for a preliminary investigation of Facies C2 and D, and to a lesser extent C1.

As a result of all these experiences, and in the light of the need for sound geological evidence of the types and proportions of facies present on site, the above methods, with the exceptions of those which provide cored boreholes, are not recommended for drilling the gravelly parts of the pebble beds, but instead, two methods of exploration are suggested, namely: (a) the excavation of trial trenches and (b) down-the-hole photography.

Trial trenches. The digging of long, narrow, 1 m wide, 2-3 m deep trial trenches by a backactor attached to an excavator is appropriate where the beds are gently dipping and can be shored by planking, for this enables a considerable vertical depth of succession to be viewed by the engineer and logged by the geologist: about 11 m depth at a 5 degrees dip and 20 m at a 10 degrees dip for every 100 m length. It also permits a restricted inspection of lateral variability in any one bed: approximately 25 m at a 5 degrees dip and 10-12 m at a 10 degrees dip. Such trenches have proved to have safe side slopes and to remain open for inspection for considerable periods of time in all but the loosest of gravels. Besides giving the geologist details of the facies and the succession, the state and depth of weathering of the formation can also be ascertained.

Notwithstanding the above, particular care should be taken with the safety aspects of examining such trenches. Benching of the rear section of the trench would be useful. Lining of those parts of the trenches not currently under investigation would obviously increase the safety factor, but would temporarily obscure the geology.

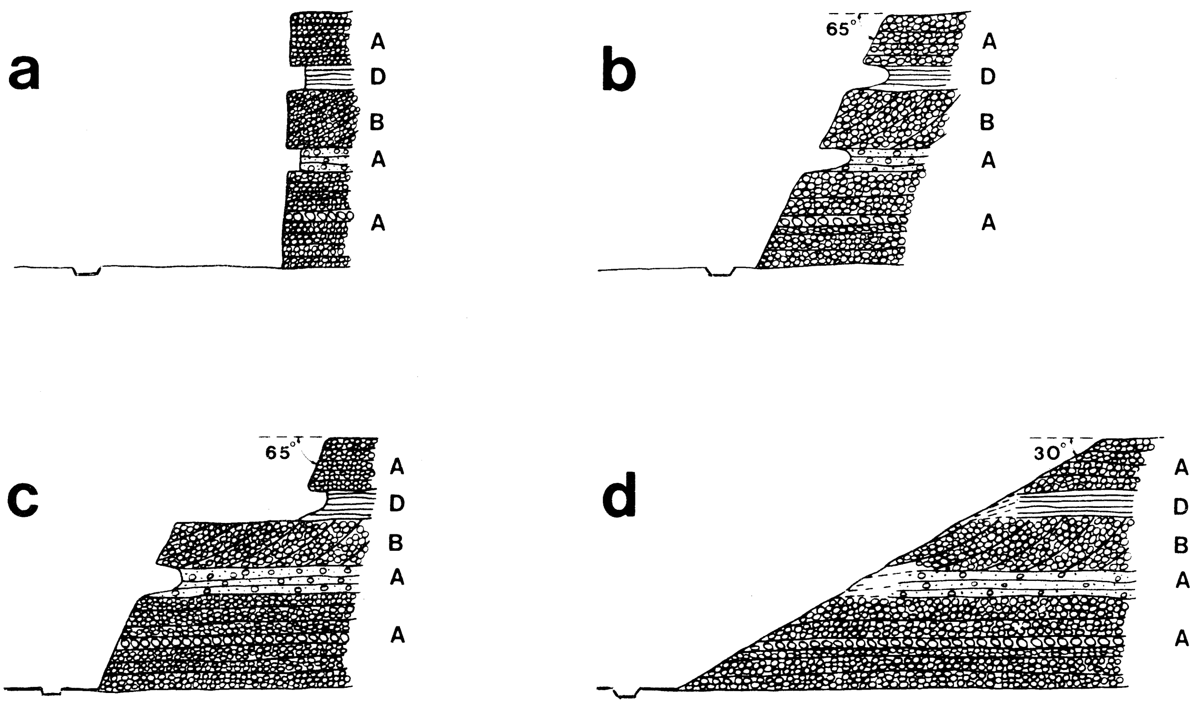
Down-the-hole photography. This has been perfected and used extensively at Hales Almington quarry (Rae, 1976). The succession has been proved there, using a RB 27 RT percussion rig to drill rough 200-225 mm diameter holes at a rate of 3-4.5 m per hour, falling to a 2 m per hour in quartzose conglomerate, down to a maximum depth of 45 m, whereupon drilling becomes laborious. Experience shows that in the Hales-Almington area a lining is not needed and that only one hole in forty is troublesome and has to be abandoned. The holes are then photographed every metre in black and white and in colour, using a 35 mm camera with a wide angle lens and a flash unit, the whole apparatus being activated by an airline, and shielded by a metal drum. The use of Agfa Goldseal 80ASA film produces satisfactory photographs. From the evidence shown to the authors, it is possible to identify and measure the thickness of the gravelly facies and sometimes distinguish Facies A and B, and also to recognise Facies C1, C2 and D, from both the photographs and the drill chippings. Based on this information, a geological succession can be drawn up in a conventional manner, preferably using graphic logging display systems. As an improvement, the authors suggest that a black and white metric scale attached to the outside of the metal shield could be lowered with the camera, for the foreshortened views of the sides of the hole are sometimes difficult to scale. Details of the cost of this technique are not available but it is considered to be relatively inexpensive. In other connections, downhole circuit television has been used and videorecordings are possible. Instead of the camera, perhaps an introscope (inverted periscope) could be used. It should be noted, however, that a RB 27 RT percussion rig may well not be available on routine site investigations, unless it is specified in the contract.

## Problems in the Design of safe Side Slopes in Cuttings in the pebble beds

Depending on the degree of cementation, and ignoring the subordinate argillaceous facies, the pebble beds can be classified in general either as a cohesionless gravel or sand with gradation between the two, or as a rock, varying from weak to moderately strong where affected by silicification or other mineralisation, e.g. barite in and near fault planes. With a more stereotyped cohesionless material, standard penetration tests can be conducted to obtain a measure of the angle of shearing resistance, using standard published empirical relationships (various authors in Anon (ed.) 1974. However, as previously noted, standard penetration testing of the pebble beds in the area under question appeared to give wholly misleading results, therefore inferred angles of shearing resistance could be grossly inaccurate. Likewise, it was totally impossible to obtain undisturbed samples from these beds for subsequent laboratory testing. Therefore, parameters for insertion into stability analyses could not be derived. One site investigation contractor concluded that, because of the drilling problems already cited, there was little useful information from traditional soil surveys upon which safe side slopes could be based. In his report (Tarmac Construction Ltd., 1971) he reviewed the whole spectrum of slope design in the pebble beds in a few sentences, concluding that "assuming no cementation, safe slopes will be of the order of 1 (vertical) to 2 (horizontal). On the other hand, assuming well-cemented pebble beds, safe slopes could be almost vertical". An example was quoted at Totmonslow (SJ 994.396), where a railway cutting 10 m in depth and over forty years old was said to have apparently stable slopes of 3 in 1 (i.e. 71.5° - actually found to be 85° by the writers), despite the fact that the slopes were badly weathered and bore signs of a few mass-flow movements.

Cox (personal communication) also favoured near-vertical slopes, since he considered the main problem to be that of rainwash. He recognised that if a slope were too flat, heavy rain would cause gully and sheetwash erosion. On the other hand, the present authors recognise that, on very steep slopes, cobbles and pebbles of high sphericity and roundness tend to loosen, fall, bounce and roll onto the carriageway, where they could become lethal in effect (plate 11, fig. b). A vehicle which strikes a cobble at speed is induced to swerve and a pebble may become a high velocity projectile. To prevent cobbles and pebbles falling onto the carriageway, a variety of rock fall traps has been contemplated: ditches, rock fences and the provision of matting surfaces. A modest trap was incorporated into the widened verge of the M6 in the Kingswood Bank section (plate 11, fig. b), but this would probably not be effective if the slopes were high and, or near, vertical. The general aim is to provide stable slopes as far as practicable, and then to arrest or catch any pebble that is dislodged.

Some of the possible slope configurations are illustrated in text-fig. 7. These are based on




A, B and D are facies within the pebble beds, described in the text, pp. 245-253.

Text-fig. 7. Possible configurations of side slopes for road cuttings within the pebble beds.

the examination of outcrops in the area and also upon hypothetical concepts. The vertical or near-vertical slope, text-fig. 7a, has already been dismissed, as it would produce conditions dangerous to traffic. The 65° slope, text-fig. 7b, is the profile adopted for the M6 motorway in the Trentham area and has proved to be stable in the twenty years since its construction. For a relatively deep cut, in excess of 12 m), the with-berm solution shown in text-fig. 7c could be applied. Material rolling from the upper section would tend to be arrested by the berm surface (text-fig. 4, north end) and falling cobbles and pebbles from the lower section would be caught in the rock trap at the base. Further attention might be given to the design of such a trap. The considerably flattened slope shown in text-fig. 7d (30° or less) would result in a greater land-take in a deep cut, but would be more suitable for shallow cuts (less than 6 m in depth). This obviates the problem of pebbles and cobbles rolling, since the slope is less than the inferred angle of rest of the pebbles. The increased cost of the land-take could be offset by the provision of an increased quantity of largely suitable material available for embankments, etc. If the slope were topsoiled and grassed, there would be no problem of gullying due to rainwash, nor one of rolling cobbles and pebbles.

In some cases, there are several possible solutions to the same problem and the one adopted in any cutting might relate not to the slopes but to the additional economic benefits which the excavation of a steeper or shallower configuration might have with respect to either reducing or increasing respectively the volume of mainly suitable construction materials. There is also the question of the aesthetics of the appearance of the cut, especially if it is a deep one, to be taken into account.

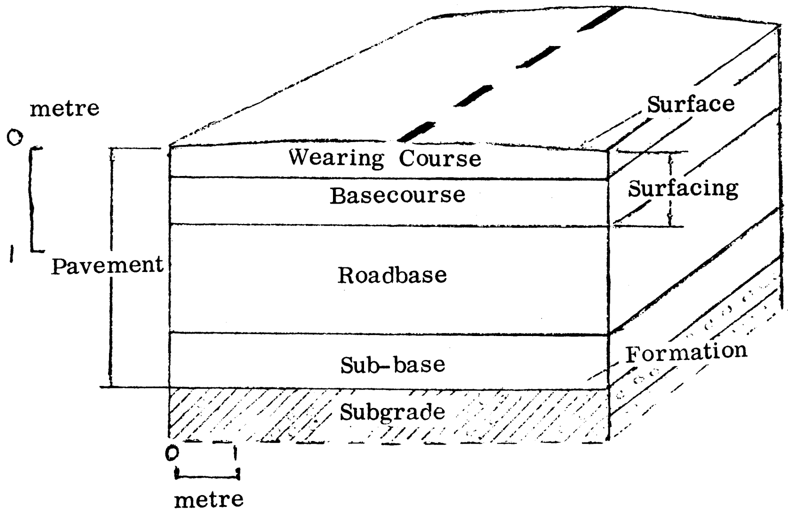
## Problems of the exploitation of the pebble beds as material for highway construction

The pre-eminence of the pebble beds as a source of aggregates is well acknowledged (Abercrombie & Jackson, 1949; Ministry of Housing and Local Government, 1950, 1952; Knill, D.C., 1963; Anon, 1968; Beaver, 1968; Harris *et al.*, 1974; Verney, 1976). Experience shows that on average 60,000 tonnes of aggregate is needed to construct every km of motorway (Knill D.C. in Knill J.C., 1978, p.168) and that approximately 60,000 $m^3$ (84,000 tonnes) of gravel can be abstracted for each acre of outcrop (150,000 $m^3$ per hectare) in the pebble beds of north Staffordshire (Ministry of Housing and Local Government 1950, 1952) compared with approximately 38,000 m (58,000 tonnes) per hectare from alluvial gravels in the middle Trent area (Mr. I. Thomas, Derbyshire County Council Planning Dept., personal communication, 1981).

The experience gained in constructing the M6 in the Trentham area proved that virtually all the on-site or off-site material from the pebble beds, apart from the most argillaceous kinds of Facies C2 and D, could be used. The pebble beds formed a suitable foundation (table 4) which was prepared without anything more than scraping and bulldozing, if attention was paid to exploiting inherent weaknesses in the rock related to sedimentary structures. There were no problems associated with bridge foundations. Spread footings were used except for some bank seats which were piled in places where they were constructed on fill, as in the area near Beech (SJ 856.382). Local quarries, themselves developed in pebble beds, provided many of the materials suitable for use as sub-base (table 5) and subsequent experience shows that they could have provided nearly all of the granular sub-base material (Types 1 and 2 of the Department of Transport specification, 1976).

Furthermore the pebble beds provide soil cement, cement-bound granular material, lean concrete, wet-mix macadam, dry-bound macadam, dense tarmacadam roadbase, dense bitumen macadam roadbase, rolled asphalt roadbase, material for paved hardshoulders and hardstrips, and wet lean concrete for sub-bases (Department of Transport, 1976). In addition 20-40 mm gravel and less than 20 mm gravel was used for concrete and porous drains, Zone 1, 2 and 3 aggregate for concrete and Zone 4 aggregate for general building purposes (see table 5 for specifications of these materials; British Standards Institution, 1965).

In the M6 Kingswood Bank cutting (text-fig. 2), it was found that a sub-base was unnecessary and the base was laid straight onto the pebble beds. Also in this cutting, the pebble beds were used to provide a cement-bound granular roadbase which is still functioning adequately.




Text-fig. 8: See explanation below.

Table 4: The construction layers of a modern road (after Knill, D.C. in Knill, J.L. (Ed.) 1978) in relation to the usage of materials from the pebble beds in road construction.

| Road Course | Thickness (mm) | Important features | Major construction materials | | Usefulness of the pebble beds |
|---|---|---|---|---|---|
| | | | Rigid | Flexible | |
| Wearing course | 13-38<br>mean c. 25 | attrition and polished stone value important (BS 812) | concrete with granite-dolerite aggregate | rolled asphalt with bitumen coated chippings | not usually suitable |
| Base-course | 38-76 mean c. 57 | | air-entrained concrete | hot-rolled asphalt | suitable for concrete but not asphalt |
| Road-base | 108-204<br>mean 154 | rock with high crushing strength allied to permeability which allows drainage | reinforced concrete | dense bitumen with aggregates | suitable for concrete |
| Sub-base | variable | as for road base: unbound aggregate | crushed rock | crushed rock | very suitable |
| Sub-grade | rock-base or soil | unconsolidated materials need to be compacted | *in situ* | *in situ* | very suitable |

Table 5: Specification for fine aggregate for concrete (including granolithic) derived from natural sources (BS 882: 1965, 1973).

| B.S. 410 1 Test sieve | | Percentage by weight passing BS sieves | | | |
|---|---|---|---|---|---|
| | | Grading Zone 1 | Grading Zone 2 | Grading Zone 3 | Grading Zone 4 |
| in | mm | | | | |
| 3/8 | 9.52 | 100 | 100 | 100 | 100 |
| 3/16 | 4.76 | 90-100 | 90-100 | 90-100 | 95-100 |
| No. | mm | | | | |
| 7 | 2.40 | 60-95 | 75-100 | 85-100 | 95-100 |
| 14 | 1.20 | 30-70 | 55-90 | 75-100 | 90-100 |
| | microns | | | | |
| 25 | 600 | 15-34 | 35-59 | 60-79 | 80-100 |
| 52 | 300 | 5-20 | 8-30 | 12-40 | 15-50 |
| 100 | 150 | 0-10 | 0-10 | 0-10 | 0-15 |

1 BS 410, 'Test sieves'
Part 1, 'Fine and medium test sieves (woven wire)',
Part 2, 'Coarse test sieves (perforated plates)'.

On-site and off-site gravels and sandstones from the pebble beds were used to construct embankments and the gravel provided a granular topping to embankments below formation level. Material from all facies, even C2 and D, was used as casual fill in innumerable instances away from the main carriageways.

In constructing the M6, off-site materials were transported from quarries at Hales-Almington, Acton, Lordsley, Trentham and Hulme. In the account which follows, the best practices of quarrying the local pebble beds at Acton and Hales-Almington are given. The descriptions of grain-size cited in the following sections are those used informally in an undefined way by the construction industry, hence the descriptions are put in quotation marks. In general the geological equivalent of any of these terms is a good deal coarser: the 'fine sand' of a quarry manager is roughly equivalent to the geologist's medium and coarse sand.

In former years, blasting was undertaken in some places to work vertical faces as high as 45 m, but a greater willingness to consider environmental issues and an enhanced regard for the wishes of local residents led to the cessation of blasting in 1974. In addition, the requirement of the Mines and Quarries Inspectorate that the maximum height of face should be 12.5 m was slowly implemented. As the size and capability of machinery increased, even the most highly cemented materials began to succumb to the scraper and ripper. Machines smaller than the 38 RB face shovel proved to be generally ineffective in digging shallow trenches and attacking soft faces, but medium and hard faces were easily worked by using a D8 or D9 bulldozer armed with a single tine (= toothed) ripper, although the quartzose nature of the material of the pebble beds renders it so abrasive that the ripper tooth has to be replaced daily and the tracks roughly once a year. These machines are now set to work on a gentle incline, breaking up the underlying rocks and bulldozing them to a heap. Thereafter, a Caterpillar 980 truck is used for load-and-carry operations up to a mobile hopper placed at a maximum distance of 100 m. Normally, this hopper is made to feed a 600 mm field conveyor belt at a rate of approximately 250-300 tonnes per hour. The conveyor system services a crushing, sorting and washing plant.

The production process sometimes begins with the pre-sorting of the gravel into large and small grades by the driver of the face shovel and the hand picking of 200 mm cobbles off the conveyor for separate and very profitable sale at £8 per tonne (October 1977). These cobbles are used to decorate bridge footings and parts of traffic islands adjacent to the motorway, where they help to inhibit jay-walking. Blocks of red mudstone are also removed, for reasons stated earlier.

Otherwise, the materials from the conveyor belt undergo a primary screening which delivers 50 mm (2 in) 'pebbles' to a jaw crusher. From thence the material is washed in a scrubber barrel, the less then 5 mm grade being flumed into a 'sand' separation plant, the less than 20 mm material being conveyed to a final screen and the greater than 20 mm grade put into closed circuit back to a gyratory crusher.

The coarse fraction undergoes a final screening and rinsing, whilst the 'sand' is washed and separated by a Lynatex hydrocyclone separator, a centrifugal dewatering device, which feeds the end-product to a classification plant which grades it for use in concreting, brickmaking and asphalt. Quality control of the asphalt 'sand' is particularly critical since the wearing course of the two slow lanes of the M6 originally incorporating glacial 'sands' was so badly worn by 1976 that it had to be replaced at great cost by material of a higher stability specification. This was produced largely from the pebble beds, stability index 2.2-3.6 on the Marshall Scale, originally considered unsuitable! Amey Roadstone Ltd. find that quality control of asphalt 'sand' is achieved best by examination of samples of material under the microscope.

Up to 20% of the pebble beds (mostly 'fine sand' and 'silt') is caught in a sump and, being unsaleable as a mass, has to be pumped into settlement lagoons. The process leads to further sedimentary differentiation of grain-size across man-made alluvial cones, and the coarser 'sands' accumulating near the inlet pipe at the head of the cone have proved to be saleable at Acton. In all these processes, a clean and assured water-supply is vital, for 1,400-1,600 litres (300-350 gallons) are needed for every tonne of product. Water is often obtained from an on-site borehole tapping a water table which lies wholly within the pebble beds. In the summer months, however, as in the drought of 1976, recycling of water from settlement lagoons is often practiced so that 20-25% of the supply is re-used.

All the wearable parts of the processing plant, the scrubber barrel, liners, chutes, screen cloths and plant pumps, need to be lined with rubber or plastic to reduce maintenance costs. The crushing of material of such hardness requires frequent adjustments to the crushing parts: a 3.25 m cone crusher fed with 25 mm - 75 mm quartzose gravel requires adjustment once a day and vital parts wear out in only seven weeks. Small crushers require their rings to be turned every two weeks and the mantle and ring changed after three weeks.

Production from large quarries such as Hales-Almington runs to 2,000 tonnes per day, 250 tonnes being of asphalt 'sand', 300 tonnes of concrete 'sand' (£1.60 per tonne ex-works) and building 'sand' (£1.40 per tonne) and 1,200-1,450 tonnes of gravel £1.80 - £2.10 per tonne) (all at October 1977 prices).

## Conclusions

Geological information concerning the north Staffordshire area has increased greatly since the first geological survey in the 1850s but the sum total of this has been somewhat unhelpful to the highway engineer. Even six-inch to one mile mapping carried out in the early and middle 1960s is not yet fully available due to higher priorities being given to other work. The new memoir, which would give useful details of local exposures, has not yet been published. The study of the petrography of the pebbles in the pebble beds helps to explain weaknesses in the rock and the quality of the materials as aggregate, but arguments concerning the tectonic setting or source of the pebbles, although of intrinsic interest, are irrelevant to the problems of the engineer.

Detailed sedimentological analysis reveals the presence of two gravelly facies, a spectrum of sandy sub-facies, and a sand-silt-mud facies. The four main facies are found to vary rapidly in both vertical and lateral sequence in a largely unpredictable manner. The results of exercises aimed at finding mean variations of the distribution of facies are only of general use. Interpretation of sedimentary process and environment enables beds to be referred to the growth of various types of longitudinal, diagonal and transverse bars in a gravelly or sandy braided river environment, but in the present state of knowledge, this analysis merely predicts that great vertical and lateral variability is to be expected especially in the gravelly parts of the sequence in hitherto unexplored parts of the pebble beds outcrops.

Despite the relatively large volume of geological information now available, the highway engineer has considerable problems in designing routeways and cuttings in the pebble beds. Local site investigations are necessary, but traditional methods such as shelling and rotary drilling are useful for analysing the sandstones, but are unsatisfactory for investigating the gravelly facies. Trial trenches and down-the-hole photography carried out in percussion boreholes appear to be promising techniques for further evaluation and, used together, would cover the investigation of strata in the deepest projected road cuts. The problem of designing safe side-slopes in pebble beds outcrops is difficult since, contrary to experience in other formations, geotechnical analysis is not realistic without further research. Undisturbed samples cannot be obtained and results of standard penetration blow counts are unreliable except in the sandstones. Nevertheless, examination of outcrops and hypothetical considerations have enabled various slope configurations to be drawn. A vertical or near-vertical slope is not recommended, because of the potentially lethal effect of falling cobbles and pebbles. A 65° slope, in conjunction with an improved rock trap, would appear to be satisfactory. For deeper cuts in excess of 12 m in depth, the same configuration, with the addition of a berm, could be adopted. For shallower cuts, a 30° slope would be satisfactory, but this would have to be soiled and grassed to prevent rain erosion. Several slope solutions are possible and the one chosen might rest upon economic considerations, which are very important, bearing in mind that almost all of the pebble beds can be used for embankment construction, etc. Therefore, the cut/fill relationship along the route of a projected roadway could be varied to suit, with the proviso, of course, that widening cuts would result in increased costs of land-take. However, a very precise cost-balancing operation could result in considerable economic benefits on a large scheme. Reduction in transport costs would be appreciable if indigenous fill material were used *ab initio*.

There are no further problems with the material, which is almost entirely 'suitable' for a wide range of construction purposes related to highways. Excavation is normally by scraper or bulldozer, though some harder beds may have to be ripped.

A further discussion of the environmental aspects of highway construction will be found elsewhere in this issue of the Mercian Geologist.


## Acknowledgements

The work described was carried out partly in the Derbyshire Sub-Unit of the Midland Road Construction Unit of the Directorate General of Highways, Department of Transport, and the paper is published by permission of the Director General.

The authors are indebted to Messrs P. Vincent and M.R. Rae, MBE, of Amey Roadstone Ltd., Mr. J. Atkin of Coopers Ltd., Mr. J. Warrilow of Staffordshire County Council Planning Department, Mr. B. Cox, Assistant County Surveyor, Staffordshire County Council and Dr. R.J. Steel, University of Bergen, Norway. Dr. E. Derbyshire, University of Keele, assisted in ensuring photographic coverage. Mrs. D.B. Thompson kindly provided secretarial help. The authors thank Mr. S. Walthall for a critical review of an early draft of the manuscript.



D.S. Buist, MA, PhD, MICE,
formerly with Derbyshire Sub-Unit,
Midland Road Construction Unit,
now Materials Engineer with
Derbyshire County Council Surveyors Dept.,
Soils and Materials Laboratory,
Ripley Road, Ambergate,
Derbyshire DE5 2ER

D.B. Thompson, BA, MSc, FGS
Department of Education
The University
Keele, Staffs. ST5 5BG

## References


ABERCROMBIE, P. & JACKSON, H. (Eds.) 1949. *North Staffordshire Plan (advance copy).* London; Ministry of Town and Country Planning, 328pp.

ANON 1968. *Sources of road aggregate.* London; HMSO, 156pp.

ANON (Ed.) 1974. *European Symposium on Penetration Testing Proceedings*; vol.1, *State of the Art Report*, 215pp; vol.2(i), *General Reports and discussions*, 259pp; vol.2(ii), *Papers*; 436pp, Stockholm.

BARNES, J. & HOLROYD, W.F. 1897. On the pitting found on the Bunter pebbles at Trentham. *Trans. N. Staffs. Naturalists Field Club*, vol.31, p.134.

BEAVER, S.H. 1968. *The geology of sand and gravel.* London; Sand and Gravel Association, 66pp.

BLAIKIE, J. 1887. The Trentham gravel beds and their leadings. *Trans. North Staffs. Naturalists Field Club*, vol.21, pp.58-60.

BLUCK, B.J. 1976. Sedimentation in some Scottish rivers of low sinuosity. *Trans. R. Soc. Edinb.*, vol.69, pp.425-456.

BONNEY, T.G. 1880. Notes on the pebbles in the Bunter Beds of Staffordshire. *Geol. Mag.*, vol.7, pp.404-7.

BONNEY, T.G. 1900. The Bunter Pebble Beds of the Midlands and the source of their materials. *Quart. Jl. geol. Soc., Lond.*, vol.56, pp.287-306.

BOTT, M.P.H. 1964. Formation of sedimentary basins by ductile flow of isostatic origin in the upper mantle. *Nature*, vol.201, 1082-1084.

BRITISH STANDARDS INSTITUTION 1943. *BS 410. Test Sieves Part 1 Fine and medium test sieves (woven wire); Part 2 Coarse test sieves (perforated plates).* London; British Standards Institution.

BRITISH STANDARDS INSTITUTION 1953. *BS 812. Sampling and testing mineral aggregates, sands and fillers.* London, British Standards Institution.

BRITISH STANDARDS INSTITUTION 1954. *BS 882, 1201. Concrete aggregates for natural resources.* London, British Standards Institution.

BRITISH STANDARDS INSTITUTION 1965. *BS 882. Specification for aggregates for natural resources for concrete (including granolithic)*, London, British Standards Institution.

BRITISH STANDARDS INSTITUTION 1967. *BS 1377. Methods for testing soils for civil engineering purposes.* London, British Standards Institution.

CAMPBELL-SMITH, W. 1963. Description of the igneous rocks represented among pebbles from the Bunter Pebble Beds of the Midlands of England. *Bull. Brit. Mus. (Nat. Hist.) Mineralogy*, vol.2, pp.1-17.

CANTRILL, T.C. 1913. Estheria in the Bunter of South Staffordshire. *Geol. Mag.*, vol.50, pp.518-19.

DEPARTMENT OF TRANSPORT 1976. *Specification for road and bridge works.* London; HMSO, 194pp.

EDMUNDS, W.M. & MORGAN-JONES, M. 1976. Geochemistry of groundwaters in British Triassic sandstones: the Wolverhampton-East Shropshire area. *Q. Jl. Engng. Geol.*, vol.9, pp.73-101.

FITCH, F.J., MILLER, J.A. & THOMPSON, D.B. 1966. The palaeogeographic significance of isotopic age determination on detrital micas from the Triassic of the Stockport-Macclesfield district; Cheshire. *Palaeogeog., Palaeoclimatol., Palaeocol.*, vol.2, pp.281-313.

FORSHEW, K. 1971. *Borings in Bunter Pebble Beds.* Matlock; Midland Road Construction Unit, Derbyshire Sub-Unit, 7pp.

FRANCIS, H.W.A. & TOMLINSON, M.J. 1972. *Site investigation for motorways. Public works Congress, session under the auspices of the Institution of Highway Engineers*, Paper 12, 15th November.

GEOLOGICAL SURVEY OF GREAT BRITAIN 1962. *Summary of Progress.* London, HMSO for Geol. Surv. Grt. Brit., 91pp.

GIBSON, W. 1905. The geology of the North Staffordshire Coalfield. *Mem. geol. Surv. E & W*, London; HMSO, 523pp.

GIBSON, W. & WEDD, C.B. 1905. The geology of the country around Stoke-upon-Trent (2nd Edit.). *Mem. geol. Surv. E & W*, London, HMSO, 85pp.

GIBSON, W. 1925. The geology of the country around Stoke-upon-Trent (3rd Edit.). *Mem. geol. Surv. E & W*, London; HMSO, 112pp.

HARRIS, P.M., THURRELL, R.G., HEALING, R.A., & ARCHER, A.A. 1974. Aggregates in Britain. *Proc. R. Soc.*, Lond., Ser. A, vol.339, pp.329-353.

HARTLEY, A. 1974. A review of the geological factors influencing the mechanical properties of road surface aggregates. *Q. Jl. Engng. Geol.*, vol.7, pp.69-100.

HEIN, F.J. & WALKER, R.G. 1977. Bar evolution and development of stratification in the gravelly, braided, Kicking Horse River, B.C., *Can. Jl. Earth Sci.*, vol.14, pp.562-570.

HULL, E. 1869. The Triassic and Permian rocks of the Midland Countries of England. *Mem. geol. Surv. E & W*, London; HMSO, 127pp.

KNILL, D.C. 1978. *Aggregates, sand, gravel and constructional stone.* Ch.8, pp.166-195 in Knill, J.L. (Ed.) 1978.

KNILL, D.C. 1963. The geology of the sand and gravel deposits of Great Britain, their deposition, distribution and utilisation. *Cement Lime and Gravel*, vol.38, pp.311-316. London; Sand and Gravel Association.

KNILL, J.L. (Ed.) 1978. *Industrial geology.* Oxford; Oxford University Press, 344pp.

McLEAN, A.C. 1978. Evolution of fault-controlled ensialic basins in northwestern Britain. pp.325-346 in BOWES, D.R. and LEAKE, B.E. (Eds.). *Crustal Evolution in Northwestern Britain and Adjacent Regions.* Geol. J. Spec. Issue No.10.

MIALL, A.D. 1977. A review of the braided river depositional environment. *Earth-Sci.-Rev.*, vol.13, pp.1-62.

MINISTRY OF HOUSING AND LOCAL GOVERNMENT 1950. *Report of the Advisory Committee on Sand and Gravel (the "Waters" Committee): Part 3, Trent Valley: Part 4, West Midlands.* London; HMSO, 81pp.

MINISTRY OF HOUSING AND LOCAL GOVERNMENT 1952. *Report of the Advisory Committee on Sand and Gravel (the "Waters" Committee): Part 10, North West Gravel Region.* London; HMSO, 38pp.

MOLYNEUX, W. 1861. Local Geology: Trentham. *Potteries Mech. Mag.*, vol.2, pp.5,65,93,135,151,185,206.

MOLYNEUX, W. 1867. On the Gravel Beds of Trentham Park. *N. Staffs. Naturalists Field Club (Report for 1866). Geol. Mag.*, vol.iv, pp.173-4.

MOLYNEUX, W. 1876. The Trentham Gravel Beds. *Proc. Dudley and Midland Geol. Soc. and Field Club*, vol.3, p.32.

PATTISON, J., SMITH, D.B. & WARRINGTON, G. 1973. A review of late Permian and early Triassic biostratigraphy in the British Isles. pp.220-260 in LOGAN, A. and HILLS, L.V. (eds.). The Permian and Triassic Systems and their mutual boundary. *Canadian Society of Petroleum Geologists Memoir*, No.2, 766pp.

PIPER, D.P. & ROGERS, P.J. 1980. Procedure for the assessment of the conglomerate resources of the Sherwood Sandstone Group. *Miner. Asses. Rep. Inst. geol. Sci.*, No.56, London, HMSO for IGS, 11pp.

RAE, R.M. 1976. (Unpublished address to members of the Sand and Gravel Association). Shrewsbury; Amey Roadstone, 7pp.

ROBINSON, P.L. 1971. A problem of faunal replacement in Permo-Triassic continents. *Palaeontology*, vol.14, pp.131-153.

RUST, B.R. 1979. Coarse alluvial deposits. pp.9-22 in Walker, R.G. (Ed.) *Facies Models.* Waterloo, (Ontario). Geoscience Canada, 211pp.

SLANEY, J.P. 1974. *Bunter Pebble Beds.* Matlock, Midland Road Construction Unit, Derbyshire Sub-Unit, 5pp.

SMYTH, W.W. 1862. Iron ores of Great Britain. Part IV - iron ores of North Staffordshire. *Mem. geol. Surv. E & W.* London; HMSO, pp.25-296.

STAFFORDSHIRE COUNTY COUNCIL 1969. *Sand and gravel. Report of survey.* Stafford; Staffs. County Council, 44pp.

STEEL, R.J. & THOMPSON, D.B. (In preparation). Structure and texture in Triassic (?Scythian) braided stream conglomerate in the Pebble Beds of the Sherwood Sandstone Group in North Staffordshire, England.

TARMAC CONSTRUCTION LTD. (GEOTECHNICAL DIVISION) 1971. *Report on soil survey for the Stoke-Derby Motorway M6-M1.* Wolverhampton; Tarmac Ltd.,

THOMPSON, D.B. 1970. Sedimentation of the Triassic (Scythian) red pebbly sandstones in the Cheshire Basin Sandstones and its margins. *Geol. Jl.*, vol.7, pp.183-216.

VAIL, P.R., MITCHUM, Jr., R.M., TODD, R.G., WIDMIER, J.M., THOMPSON, S., SANGREE, J.B., BUBB, J.N., & HAFIELD, W.G. 1977. Seismic Stratigraphy and global changes of sea level. pp.42-212 in PAYTON, C.E. (Ed.) Seismic stratigraphy. Application to Hydrocarbon Exploration. *Amer. Assoc. Petrol. Geol. Mem. 26.*

VARIOUS AUTHORS 1974. Proceedings of the European Symposium on penetration testing. Stockholm; pp.

VERNEY, R.B. 1976. *Aggregates: the way ahead.* London; HMSO, 118pp.

WAKELING, T.R.M. 1972. The planning of site investigations for highways. *Q. Jl. Engng. Geol.*, vol.5, pp.7-14.

WALKER, R.G. (Ed.) 1979. *Facies Models.* Waterloo (Ontario); Geol. Assn. Canada, 211pp.

WARRINGTON, G., AUDLEY-CHARLES, M.G., ELLIOTT, R.E., EVANS, W.B., IVIMEY-COOK, H.C., KENT, P., ROBINSON, P.L., SHOTTON, F.W. & TAYLOR, F.M. 1980. A correlation of Triassic rocks in the British Isles. *geol. Soc. Lond.*, *Special Report*, No.13, 78pp.

WEDD, C.B. 1899. On barium sulphate as a Cementing Material in the Bunter Sandstone of North Staffordshire. *Geol. Mag.*, Decade IV, vol.6, pp.508.

WILLS, L.J. 1948. *The palaeogeography of the Midlands* (2nd Edit.), Liverpool; Liverpool Univ. Press, 147pp.

WILLS, L.J. 1951. *A palaeogeographical atlas.* London and Glasgow; Blackie, 64pp.

WILLS, L.J. 1956. *Concealed Coalfields.* London and Glasgow; Blackie, 208pp.

WILLS, L.J. 1970. The Triassic Succession in the central Midlands in its regional setting. *Q. Jl. geol. Soc.*, Lond., vol.126, 225-85.

WILLS, L.J. 1976. The Trias of Worcestershire and Warwickshire. *Rep. Inst. Geol. Sci.*, No.76/2, 211pp.

WILLS, L.J. & SARJEANT, W.A.S. 1970. Fossil Vertebrate and Invertebrate tracks from boreholes through the Bunter Series (Triassic) of Worcestershire. *Mercian Geol.*, vol.3, pp.399-414.

WILSON, A.A. 1962 in *Summary of Progress.* Geol. Surv. Great Britain. London, HMSO, 91pp.

ZIEGLER, P.A. 1981. *Evolution of sedimentary basins in Northwest Europe.* pp.3-39 in Illing, L.V. & Hobson, G.D. (Eds.) *Petroleum Geology of the Continental Shelf of North west Europe.* London, Heyden for the Institute of Petroleum, 521pp.

# CONSERVATION, PLANNING AND OTHER ISSUES RELATING TO THE GEOLOGY OF THE CONSTRUCTION OF HIGHWAYS ACROSS AREAS UNDERLAIN BY PEBBLE BEDS OF THE SHERWOOD SANDSTONE GROUP

by

David B. Thompson

## Summary

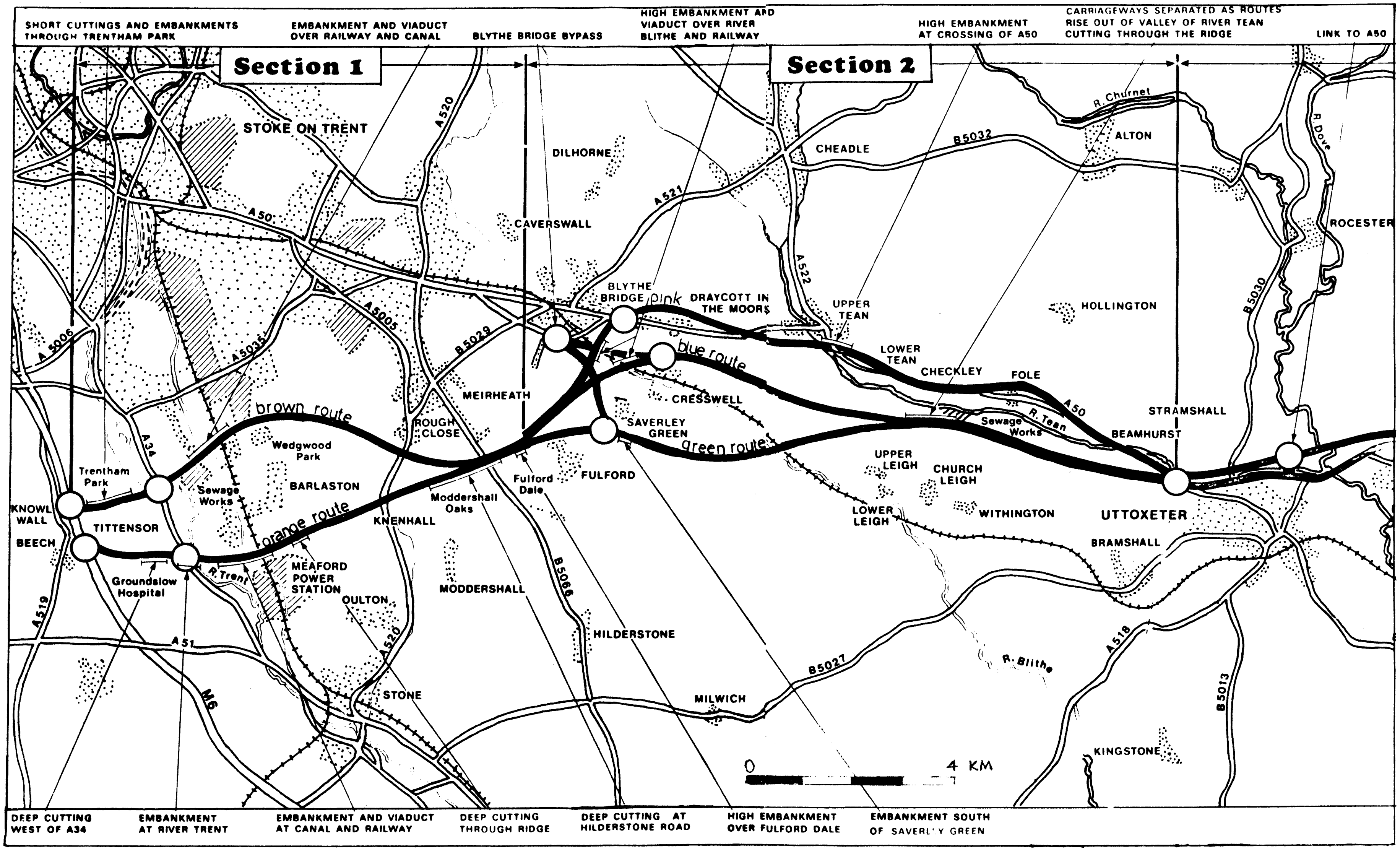
The paper describes the problems associated with the planning of the A564 Stoke-Derby road across the pebble beds of the Sherwood Sandstone Group in north Staffordshire. Planning the supply of materials to major roadworks from existing quarries may need 15 years foresight with respect to obtaining planning consent, prospecting resources, organising the working of quarries and ensuring the commitment of sufficient capital. Public consultation over the geological and other reasons for the proposed routes is nearly obligatory, and the restoration of land to agriculture or to public use is much desired. The origin of the Park Hall Country Park near Longton is described to show how the geological features of the pebble beds in an area scarred by haphazard quarrying and tipping have been utilised to construct a major public amenity in an area not hitherto well endowed. Since virtually all parts of the pebble beds are suitable for road construction an outline analysis is made of the cost benefits of supplying such materials from on-site sources along the projected highways compared with off-site sources in working, or abandoned, quarries. Whilst many of the present methods of planning and managing geological site investigations in areas of sandstone outcrops may be adequate, those in conglomerates fail to supply reliable information and are costly.

## Introduction

The present article, although self-contained, is best read in conjunction with the previous one by Buist & Thompson (1982, this volume, pp. 241-268) which discussed the sedimentology, engineering properties and exploitation of the pebble beds of the Sherwood Sandstone Group in relation to the experience of constructing the M6 motorway and preparing for the M64 (now abandoned) and the A564 Derby-Stoke link road.

In north Staffordshire there has been considerable discussion of the provision of new roads to relieve traffic congestion which arises at many points on the A50 between Stoke and Derby, for example at Blythe Bridge and Tean (text-fig. 1). Preliminary geological investigations by the Midland Road Construction Unit (MRCU) were started in 1971 and the announcement of the preferred

Mercian Geologist, vol. 8, no. 4, 1982
pp. 271-284, 4 text-figs., 1 table




Text-fig. 1: Possible routes for the M64 (Stoke-Derby) motorway in its western part (section 1, M6 at Beech to Fulford; section 2, Fulford to Uttoxeter, to illustrate problems associated with the planning of embankments and cuttings largely in pebble bed rocks, and environmental problems (Ministry of Transport, 1976). The construction of the M64 has been abandoned but its relative costs at 1976 prices were: Brown Route, 140 acres, 10.1 km, £18.5 million; Orange Route, 130 acres, 9.15 km, £18.5 million. The A564 trunk road is to be built and will largely follow the Brown and Blue Routes.

routes was made in November 1979 (brown and blue sections, text-fig. 1). Both the previous paper (Buist & Thompson, 1982) and this note describe methods which will contribute significantly to the cost-benefit analysis of the problems which have arisen in connection with these projects. The particular parts of the M64, M6 and A564 which cross pebble beds in north Staffordshire lie between Blythe Bridge and the M6 near Beech (text-fig. 1), but the supply of materials for the new roads may involve quarries within a much wider area. Of the many possible routeways of the M64 and A564 through this area put forward by the MRCU, only two, the Orange and Brown Routes (text-figs. 1 & 2), were seriously considered. In addition to the three problems identified by Buist & Thompson (1982), four further problems are discussed here:

1. Conservation and planning issues surrounding the working of extensive quarries in the pebble beds in the neighbourhood of motorways like the M6, or link roads like the A564.

2. The possibility of restoring land, which has been quarried for long period in a haphazard way, to public use.

3. The availability and cost of off-site construction material from pebble bed outcrops in relation to the practical use of on-site resources.

4. The extent to which present methods of site-investigation are cost effective.

It is emphasised here that the views expressed in this paper are those of the author alone and are not those necessarily of his co-author of the previous paper or of the staff of the East Midlands Geological Society.

## An outline of the nature and origin of the pebble beds of the Sherwood Sandstone Group

These rocks form the lower undefined part of the Cannock Chase Formation in the east and the Chester Pebble Beds Formation in the west (Warrington *et al.*, 1980) at, or close to, the base of the Trias. The old Geological Survey Great Britain maps give a clear indication of the outcrops of the conglomerates and pebbly sandstones under their designation '$f_2$'. Throughout this paper the phrase 'pebble bed(s)' refers to strata of the Sherwood Sandstone Group, for example the Chester Pebble Beds Formation. The distribution of the pebble beds is widespread in the east and west Midlands (text-fig. 3) and most of what is discussed here, although derived from experience gained from north Staffordshire, is directly applicable to the whole area. The relationship of the pebble beds to the rest of the succession is shown in text-fig. 2.

The pebble beds of the Sherwood Sandstone Group have been shown to consist of the following facies (Buist & Thompson, 1982):

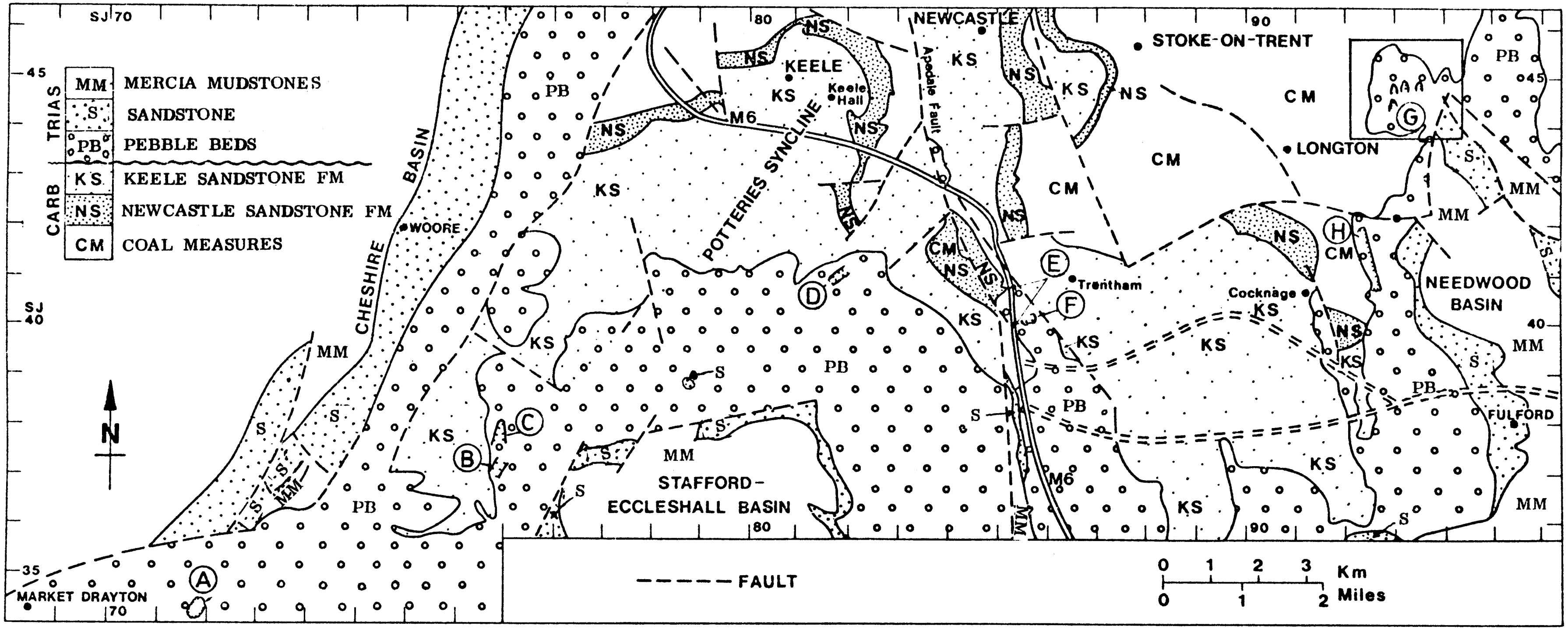
Facies A Flat stratified pebble conglomerate or gravel representing former longitudinal or diagonal gravel bars in a braided river.

Facies B Cross-stratified pebble conglomerate or gravel representing the downstream avalanche surfaces of such bars, or the migration of transverse gravel bars.

Facies C A spectrum of cross-bedded sandstone, grading from medium to fine pebbly sandstones (type $C_1$), to medium to very fine argillaceous micaceous, usually pebbleless sandstones (type $C_2$), representing the migration of sandwaves and megaripples and transverse bars in a sandy braided river.

Facies D Interbedded fine-grained argillaceous sandstone, siltstone and mudstone indicating the settling of argillaceous sediment from suspension in areas of slackwater at periods of high to moderate discharge, or overall settling of fines at low discharge, in gravelly or sandy braided rivers.

The lowest part of the pebble beds often consist of Facies $C_2$ and $C_1$, but the succession coarsens upwards by the addition of Facies A and B to $C_1$ until the main productive gravel horizons are reached. Thereafter the succession fines upwards by loss of Facies A and B and




Text-fig. 2: Geological map of north Staffordshire to show possible lines of the M6 motorway (now abandoned) and the A564 link road over pebble bed outcrops, and the positions of quarries which were available at the time of construction of the M6 motorway. The northerly route is the Brown Route, the southerly the Orange Route.

A = Hales-Almington Quarry
B = Lordsley Quarry
C = Willoughbridge Quarry
D = Acton Quarry
E = Trentham M6 Motorway Cutting
F = Kingswood Bank Quarry
G = The Park Hall Country Park quarries (see text-fig. 4, the position of which is located by the rectange on the NE of the map)
H = Quarries between Normacot and Lightwood

the increase in Facies $C_1$ and eventually $C_2$ and D, until the Upper Mottled Sandstone, (Wilmslow Sandstone Formation) '$f_3$' is reached. This distribution probably reflects a sedimentological response to first increasing then decreasing intraplate extensional basin-forming tectonic events (Ziegler, 1978), though Wills (1970; 1976) maintains that it is climatically controlled, whilst others provide the basis of possible explanations which involve worldwide changes of sea-level, hence local changes of base-level (Vail *et al.*, 1977).

## Conservation and Planning Issues

The planning authorities long ago forecast that the high quality sands and gravels of the pebble beds of north Staffordshire would play a vital part in the development of the post-war road network of the northwest Midlands and south Lancashire (Beaver in Abercrombie & Jackson, 1949, p. 83). At that time they recognised no planning or conservation problems:

> "There is so far as we know, no serious local objection to the gravel industry as there is in some parts of the country on grounds of conflict with agriculture, amenity, or town planning: but if there were it should in our view be strongly resisted, for the industry occupies a relatively small amount of land owing to the depth of the quarries, and moreover it plays a very vital part in the economy ..."

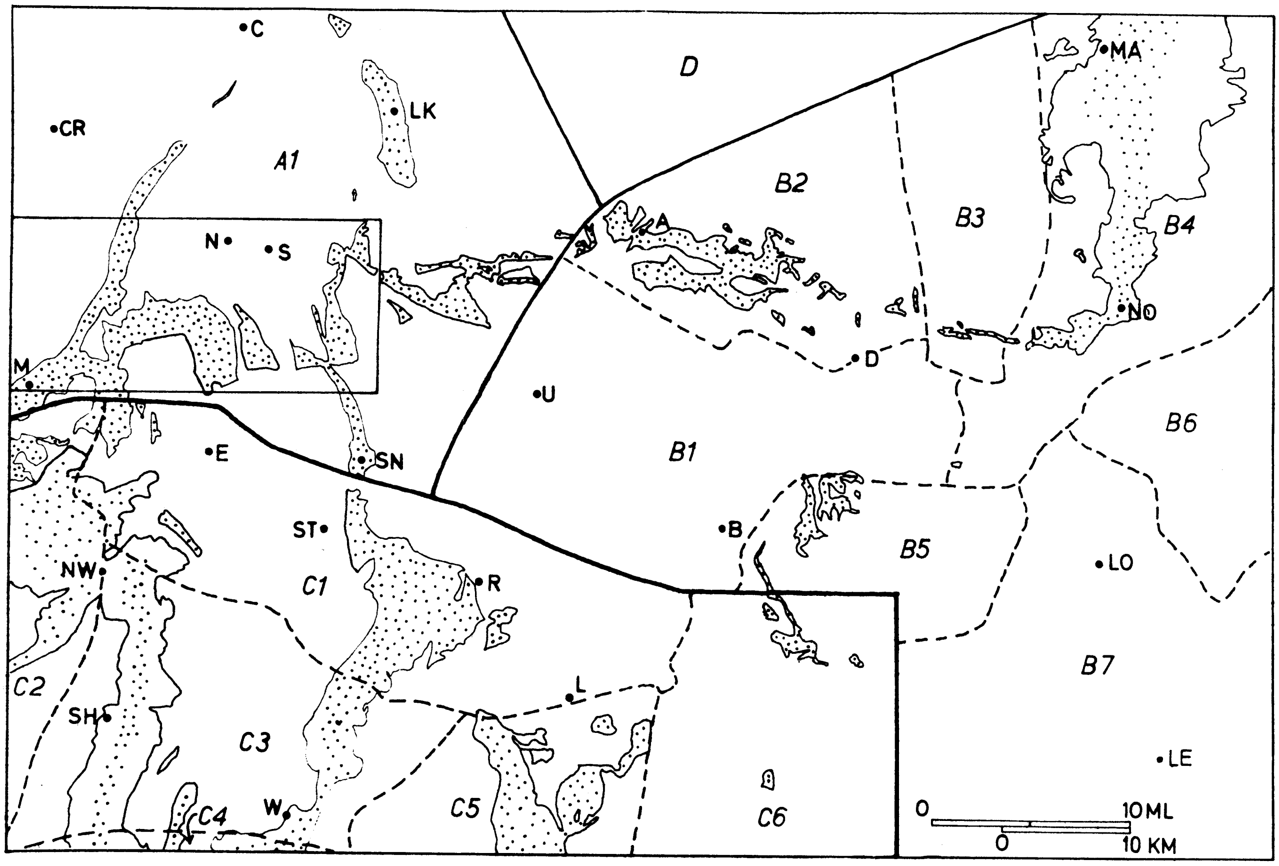
Forecasts of demand for sand and gravel derived from north Staffordshire and the west and east Midlands were reviewed by the Waters Committee (Ministry of Housing and Local Government, 1950; 1952) and were revised upwards by the planners of the County of Stafford (Staffordshire County Council, 1969) as a result of very considerably increased demand between 1950 and 1965. It was recognised that without great changes in transport costs the north Staffordshire area in particular, and the west Midlands and Trent Valley Service Areas in general (text-fig. 3), would continue to export their products to supply the insatiable demand of the conurbations of south Lancashire-north Cheshire, south Yorkshire and the Black Country (Ministry of Housing and Local Government 1950, figs. 1 and 8; 1952, Map B), as well as the needs of local areas, for example between Derby and Stoke (text-fig. 3). In a later report (Staffordshire County Council, 1969), it was acknowledged that gravel was still likely to travel from the Cheadle area to as far afield as Liverpool in the foreseeable future. In forecasting planning permission for greater allocations of land for gravel working in the period up to 1981 (*ibid.*, pp. 45-49), the planners recognised increasing land conservation problems:

> "Of the current areas that are being worked, only a very limited amount has been reclaimed and it is considered that proposals for allocations on the scale indicated by the estimated demand will need to be balanced by a much more effective and comprehensive programme for securing appropriate after-use treatment, than hitherto."

In the 1950s the after-treatment consisted of:

> "surface grading of the quarry floor and battering of the final working faces.... any humus-bearing upper layers of the soil can be respread ... as part of a continuous process of backfilling..."
> (Ministry of Housing and Local Government, 1950, p. 52).

It is common knowledge that the climate of conservation in the late 1970s and early 1980s is not that of former years. There is a greater awareness of public issues and an enhanced appreciation of environmental quality (Black, 1978, pp. 310-334). If major roadworks are to be attempted then they have to be justified both on environmental and economic grounds. Since environmental problems cost money to resolve and greatly affect the lives of the local residents, either indirectly through the paying of rates and taxes or directly through the changing of local ways of life, local communities expect to be informed of the geological and other conditions which make one series of options more desirable than others. It must be said that the public was consulted over the M64 and is being consulted over the A564 to a degree not hitherto attempted (Department of Transport, 1976).




Text-fig. 3: The outcrop in the West and East Midlands of the former 'Bunter' Rocks designated f1-f3 of the Sherwood Sandstone Group on the 1:250,000 map of the Institute of Geological Sciences. "f1", the Lower Mottled Sandstone and "f3", the Upper Mottled Sandstone, are sandy and not pebbly. "f2", the former 'Bunter' Pebble Beds, is the main source of the high quality sands and gravels and its main distribution is shown by the dotted area.

A = Ashbourne
B = Burton-on-Trent
C = Congleton
CR = Crewe
E = Eccleshall
L = Lichfield
LE = Leicester
LK = Leek
LO = Loughborough
M = Market Drayton
MA = Mansfield
N = Newcastle-under-Lyme
NO = Nottingham
NW = Newport
R = Rugeley
S = Stoke-on-Trent
SH = Shifnal
SN = Stone
ST = Stafford
U = Uttoxeter
W = Wolverhampton

The Gravel Regions designated by the Waters Committee (Ministry of Housing and Local Government, 1950; 1952) are plotted on the map as follows:

A = North West Gravel Region
B = Trent Valley Gravel Region
C = West Midlands Gravel Region
D = West Yorkshire Gravel Region

The Service Areas for Sand and Gravel are as follows:

Area B

1. Cannock Chase
2. Shropshire
3. Wolverhampton North
4. Birmingham
5. Coleshill

Area C

1. Burton and Derby
2. Derby 'Solid'
3. Unnamed
4. Nottingham
5. Unnamed
6. Unnamed
7. Leicestershire

The rectangle shows the location of text-fig. 2.

When construction materials have to be provided for such schemes, it is almost certain that they will have to come whenever possible from on-site sources or from the use and extension of existing off-site sources, for the short-term development of new quarries is unlikely (Ministry of Housing and Local Government, 1950; 1952; Staffordshire County Council, 1969).

For owners of existing quarries who may wish to respond to such possibilities, it is necessary to have planning consent for approximately 15 years ahead and to have plans for working a quarry well into the future which include the ability to increase production rapidly. One needs to have geologists involved in a team which prospects reserves and ascertains the quality of resources, whilst a manager makes tentative requests and seeks agreements concerning finance from the board of the company. Piecemeal planning is not viable these days, and proper planning takes several years (Rae, 1976).

## Issues involving the restoration of land

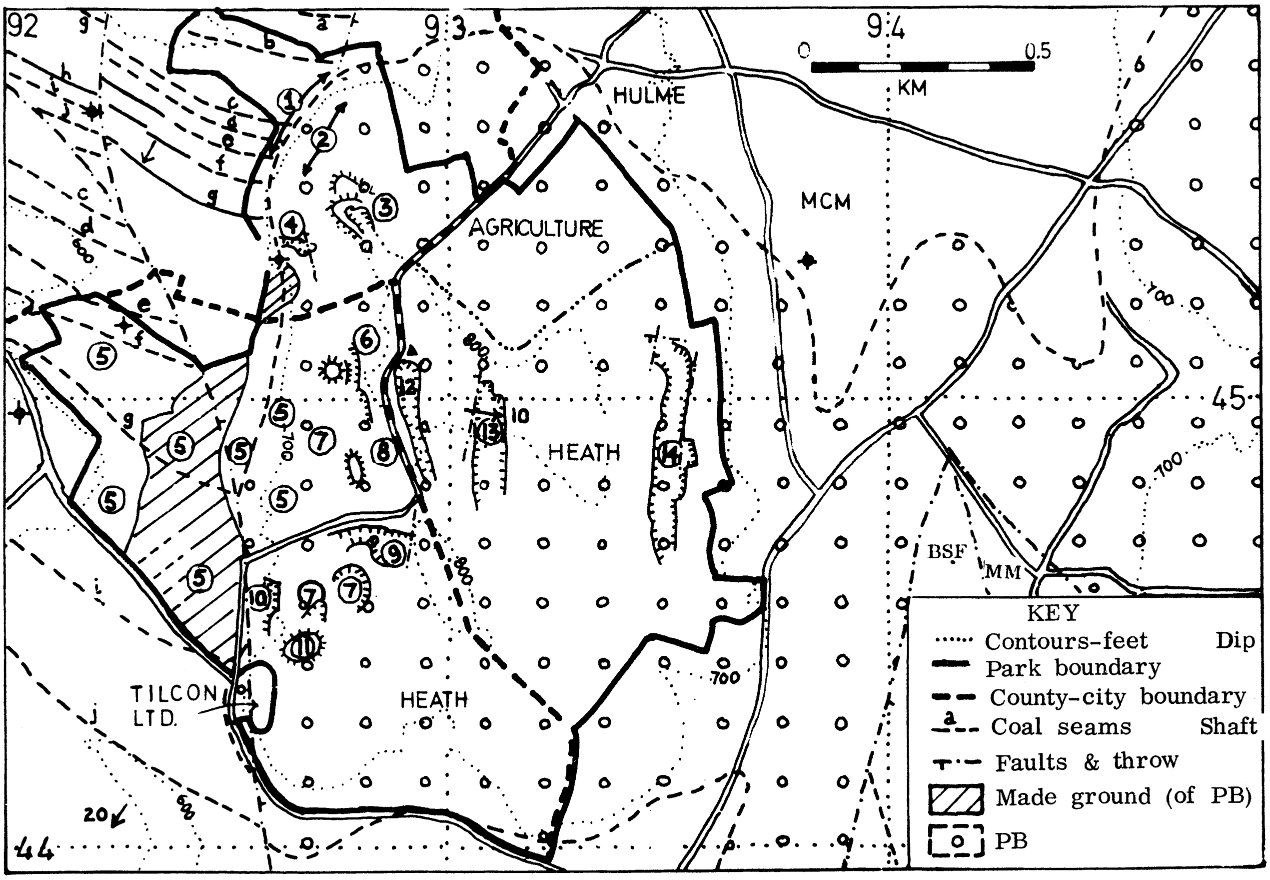
The restoration of worked out areas of pebble beds is notoriously difficult (Beaver, 1968, and pers. communications, 1980). The visual effects, particularly on a skyline, of abandoned quarry faces, piles of gullied and overgrown waste, heaps of graded product and active or abandoned headworks, are increasingly debated. The restoration of quarried-out areas, that is, those which supplied material to the M6 in the north Staffordshire area in the 1960s, is often long overdue, for example, at Lordsley and for much of the Willoughbridge area.

In some areas where restoration has been attempted, for example, at Kingswood Bank and Acton, the result is barely acceptable. Near to Willoughbridge Wells, however, the area near the former spa has been improved very acceptably by the local farmer, Mr. Wright. Often the eventual restoration of the land after quarrying has to be negotiated, partly, if not wholly, from the outset. One consortium in the Peak District which has been seeking permission to work minerals within the Carboniferous Limestone has been asked to place a bond for this purpose prior to starting extraction. In pebble bed quarries, working plans have to include long-term provision of land for disposing of the 20% waste in settlement lagoons, for these are classified as active under the Mines, Quarries and Tips Act and require strong retaining walls. With good planning, existing quarry walls can be used. Good practice involves feeding solids from the direction of the weakest wall so that it is easy to use a dragline to heap material against the wall and so strengthen it. Liquids and slurries should be allowed to run towards the most solid wall and the position of the supply pipe should be altered frequently. New settlement lagoons should be brought into use in the winter months so that the bottom of the lagoon will be sealed by the settling and compaction of argillaceous matter at a time when loss of water is not critical. Clean water should be weired off for re-use throughout the life of the lagoons which are usually drainable after 1-2 years. After they reach reinstatement level, the lagoon areas are regraded and reused, in some cases for agricultural purposes. Careful planning is needed so as not to be caught with lagoons filled to the brim with sediment and affording no possibility of recycling water (Rae, 1976).

The new Park Hall Country Park (text-figs. 2 & 4), sited largely on the pebble beds between Hulme and Weston Coyney (SJ 9345) and visited by the East Midlands Geological Society in April 1979, provides a magnificent example of what can be done, given goodwill, imagination and considerable financial support, to restore to public use a huge area (435 acres) honeycombed by waste heaps, tips, quarries and abandoned headworks. This seventeenth century heathland, resembling that of other areas underlain by pebble beds such as Cannock Chase, was initially cleared for agriculture, but became encroached upon and surrounded by the wasteheaps of the coal mines of the early industrial revolution from adits like Hulme Colliery (SJ 925.455) and larger pits like Adderley Green Colliery (SJ 922.445), Park Hall Colliery (SJ 925.437) and Mossfields Colliery (SJ 915.450). These collieries worked the seams of the Middle Coal Measures between the Mossfield and the Cockshead seams adjacent to, and beneath, the Triassic unconformity (text-fig. 4). The waste heap of the Gainmore pit shaft to the southeast of Willfield High School (SJ 926.453) has been cut through purposely in the present restoration scheme in

Table 1: The relationship between the geological features of the former quarried areas of the Park Hall County Park, Longton, and their adaptation and use as a public amenity. (See text-fig. 4 for the location of the numbered features.)

| Location on Fig. 4 | Feature of pebble beds and mineral extraction process | Amenity, adaptation and use |
|---|---|---|
| 1 | Smooth steep contours of west facing scarp; sand and gravel succession - mostly sandy. | Toboggan run. |
| 2 | Scarred steep contours of scarp. | Badger runs: nature area. |
| 3 | Natural rounded knoll at top of scarp. | "Maiden Castle" vantage point. |
| 4. | Sand quarry near base of succession (Facies C, D) restricted in extent by a major fault. Type area for studying lowest part of succession. | "The Quarry" picnic area and site of geological interest for training geologists (bedding, contrasting lithologies, faults, joints, crossbedding, etc.) |
| 5 | Old quarries, mostly of gravelly facies, worked in unorganised fashion in the early days and tipped into in an uncontrolled way. | Regraded, covered by excess sand and gravel; for use eventually as a municipal golf course. |
| 6 | Length of quarry in Facies A, B, C. | The "Kyber Pass" - part of a principal walkway. |
| 7 | Sand and gravel; Facies A, B, some C. | Picnic and kick-about bowl (similar on east side of road). |
| 8 | Eminence formed of former quarry walls; Facies A, B. | "Old Man of Hoy" vantage point. |
| 9 | Quarries in Facies A, B, C crossed by faults. | The Gulch Car Park; Picnic Hollow. |
| 10 | Abandoned headworks and approaches plus former quarry face in faces B and C | Hopper Fort and Rough Hill Car Park. |
| 11 | Abandoned mounds of unused product. | The Sand Heap (grassed). |
| 12 | Elongate quarries with fault lines controlling abandonment of mining along certain walls. | Amphitheatre: circular wall and 'bandstand' at north end. Sides of quarry smoothed and lowered. |
| 13 | North central quarry; west side fault controlled. Type area for main succession. Site of special scientific interest for study of sand and gravelly braided river deposits. | Adventure playground. Site for training geologists. |
| 14 | North eastern quarry; fault controlled. | Walk along "Canyon" to pond. |




Text-fig. 4: The restoration of abandoned quarries and sand in the area of the Park Hall Country Park, northeast of Longton (see inset on text-fig. 2). Geological boundaries are taken largely from the revision of the six inch (1:10560) sheet Staffordshire XVIII NE publihsed in 1948 and in the case of the pebble beds should be regarded as somewhat approximate especially on the east site of the Park. A key to the coal seams a - j (all in the Middle Coal Measures) is as follows (oldest first):

| | |
|---|---|
| a - Cockshead | f - Bowling Alley |
| b - Seven-foot Banbury | g - Ten Feet |
| c - Stinkers | h - Birches |
| d - Hard Mine | i - Yard |
| e - Holly Lane | j - Mossfield |

BSF = Bromsgrove Sandstone Formation
MM = Mercia Mudstone Group
MCM = undifferentiated Middle Coal Measures
PB = Pebble Beds

Ringed figures refer to the features of the Country Park which are cited and explained in table 1. The location of these features is taken from maps of the Department of Environmental Services, City of Stoke-upon-Trent.

making a major pathway. The side slopes of the tip are searched by local geology students who collect Carboniferous rocks, minerals and fossils which are otherwise rarely exposed in the Potteries Coalfield today.

In the early days of the Industrial Revolution the pebble bed outcrop was worked mainly for building sandstones of Facies C as well as for small volumes of gravel. Gravel working from the pebble beds was increased considerably in this area between 1939 and 1970, latterly in part to supply material locally whilst the M6 was making great demands upon the resources of the area. Extraction started on natural gravel outcrops to the west of the Hulme Road and, in the absence of planning controls, a vast area of shallow pits was developed. These shallow workings were then abandoned and filled for years with wholly noxious materials (sewage sludge, chemical wastes and general industrial and household rubbish) such that the environment became intolerably smelly, windswept, despoiled and groundwater polluted; and this remained so even until 1975. Extraction from the pebble beds in the 1950s and 1960s progressed downdip to the east across several small fault blocks (text-fig. 4) and to areas east of the Hulme Road, and this required exploration by borehole, the removal of considerable amounts of sandstone overburden and the initiation of numerous extensive elongate quarries aligned north-south, with faces up to 20 m high. Fortunately, however, this took place at a time when planning controls required the erection of screens of woodland, the conifers of which are now (in 1979) quite mature. During the present restoration work, the early waste-filled quarries to the west of the Hulme Road have been largely bulldozed over and other waste heaps re-surfaced with a metre-thick cover of sand and gravel which is to form the basis of a golf course. The large quarries to the east of the road have been imaginatively utilised to provide picturesque, relatively safe 'canyons' which, by means of skilful landscaping, are rendered part of the amenities of the park (table 1; text-fig. 4). Only one quarry (Tilcon Ltd.) is still working and was due to release its land in 1979, but this has not yet happened.

Lest it be thought that restoration of old workings in pebble beds outcrops like these, to something of their natural state is an easy matter, to be applied to every area, it is well to recognise that the administrative problems were great. A major county/city boundary crosses the area, 160 acres belonging to the county and 218 acres to Stoke-on-Trent and some land is still privately owned (text-fig. 4). Fortunately, before the present restoration exercise, Blue Circle Aggregates bought up most of the pits and quarries (378 acres), presumably with commercial activity in mind, but later gave the land to the city, otherwise there would have been problems of multiple ownership to deal with in addition. The reclamation scheme required the setting up of a joint management committee of the county and city councils and a working party of these two bodies plus the Countryside Commission and the Department of the Environment, the last of which eventually provided £646,000 of the total cost of £858,000. The very considerable proportion of the cost borne by the national exchequer is accounted for by the fact that Stoke is part of a Derelict Land Clearance Area.

In 1978 the restoration scheme was awarded first prize in the annual national reclamation awards scheme organised by the Royal Institution of Chartered Surveyors and the Times newspaper. In 1979 the scheme was given a further reclamation award by the Sand and Gravel Association.

## The availability and cost of on-site in relation to off-site construction materials

Details have been given previously (Buist & Thompson, 1982) of methods of exploitation of the pebble beds as material for highway construction. For reasons of confidentiality, however, nothing could be discussed there with respect to the planning of the exploitation of these materials for maximum cost-benefit in the Beech to Fulford section of the A564. Estimates for aggregate requirements for motorways and A-class roads show significant differences in amount. For motorways the average value varies from 62,500 tonnes per km (Knill, D.C., 1978, p.168) to 85,000 tonnes per km (Buist, pers. comm.). The corresponding figure for A-class roads is much less at 12,500 tonnes. Transport costs add greatly to the burden of supplying such materials from off-site areas and on-site availability during the construction of the A564 would be very welcome.

Many of the possible lines of the projected roads pass across the pebble bed outcrops for a good deal of their length and many of the proposed lines are of such varied relief that they would require cut and fill operations (see text-fig. 1). In contrast to the practice adopted with the construction of the M6 when most material came from off-site quarries up to 20 km away, the contention here is that much of the materials for the fill, the sub-base and the roadbase, for the concrete for the bridges and paths, etc. of road section 1 could be derived from on-site excavations from the pebble beds at carefully selected places along the projected highway. This would require that some of the machinery, techniques of exploration and exploitation described previously (Buist & Thompson, 1982) be assembled and employed on-site along the line of the road. The duplication of plant at several small sites is expensive and normally avoided (Knill, D.C., 1978, p.169). Temporary assembly of sophisticated plant and machinery for the processing of materials at a series of sites 10 km apart adjacent to a motorway has proved to be feasible and economic in the latest episode of the resurfacing of the M6 between Stafford and Stoke (1978-9).

The author suggests that machinery and plant could first be assembled on-site at a strategic place adjacent to the deep cutting (text-fig. 1) on the eastern part of the projected roadway between Cocknage and Fulford, the line of which lies mostly on pebble beds, so long as the planning is geared to providing water for screening and washing and to constructing cuttings of such width and slope that adequate raw materials are available for continuous processing. The costs of disposing of waste by creating settlement lagoons could probably be taken care of on-site as easily as off-site. The feasibility of such an enterprise needs to be carefully investigated, and the economics may differ at the western and eastern ends of the Fulford-Trentham stretch, for whilst the western end of the area is well supplied by efficient quarries, the eastern part is currently less well served and could benefit from the use of on-site material. For the area east of Fulford (road section 2 of text-fig. 1), the line of the projected routes lies well to south of the pebble beds, on Drift deposits and those of the Mercia Mudstone Group, and on-site materials could not be used. It is unlikely that sufficient on-site materials from section 1 of the highway will be available to furnish the construction materials needed for section 2, hence off-site materials will be required. Planning permission for working old pebble beds quarries south-east of Cheadle is held extensively by Blue Circle Aggregates, whilst other supplies are at Willington (Blue Circle) and Etwall (Redland), both in the Derby 'Solid' Service area (text-fig. 3) and hence less economical because of the distance involved. The companies may seek to open up further (abandoned) quarries in this eastern part of the route (see Staffordshire County Council Gravel Resources Report, 1969).

## Comments on current site investigation practices in the pebble bed outcrops of the Sherwood Sandstone Group

Basically the engineering geologist is in a position to advise the planning team led by the Chief Highway Engineer only after he has carried out the following investigations and evaluated their results:

(a) Made a survey of the appropriate geological, sedimentological and engineering-geological literature.

(b) Examined published and unpublished borehole records along the route greater than 15 m deep held by the Institute of Geological Sciences and those less than 15 m deep held by private companies (e.g. civil engineering contractors) and private individuals.

(c) Studied large scale 1 : 10,000 or 1 : 2500 geological maps to determine the extent of the deposits and their outcrops; drawn detailed geological cross-section across those maps to predict the sub-surface stratigraphy.

(d) Consulted the representatives of the quarrying industry on their exploration and production experience in excavating aggregates in the vicinity of the route and their ability to respond to greatly enhanced temporary demand in the vicinity of the resources area.

(e) Consulted town planners on the environmental issues at stake.

(f) Devised plans and costings for geological surveys *en route* and possible drilling and sampling programmes.

(g) Made appropriate investigations of local successions at outcrop and taken samples in order to determine the physical properties of the rocks (density; porosity; permeability; crushing, tensile and shear strengths; grain size distribution; petrography) and their geochemical environment at outcrop and within 30-45 m of the land surface.

Buist & Thompson (1982) commented on the need to improve geological mapping and the logging and description of successions, and acknowledged that site investigations would be necessary to prove a very variable and partly unpredictable succession. Whereas traditional site investigations are quite effective when dealing with sandstone successions of Facies $C_2$, problems are exacerbated with Facies $C_1$, B and A. These materials prove difficult to sample in an adequate and representative way when techniques and approaches appropriate to sandstone are applied. The majority of the comments in the previous paper show that many exploration methods are inadequate, and it was suggested that the greater use of trial trenches, down-the-hole photography or the use of an inverted periscope, would best cope with the problem of describing the facies and the succession. What was not mentioned, however, was that many of the problems of site investigation were due to: (i) continuing to use an exploration method because it was not recognised to be inadequate, and (ii) using bad or inadequately supervised drilling practices. Both these matters relate to failures of management, as do problems which relate to demands for extra payments for drilling in situations which can be construed as being beyond the terms of the legal contract. In some cases, programmes were halted because of the extra cost of the technique. What should have been borne in mind in planning is not the cost of one technique, but its cost-benefit contribution to the whole programme. Because of the variability of the lateral and vertical distribution of the pebble beds many pits and boreholes are likely to be needed, but in areas where sands greatly dominate gravels at the bottom and top of the succession, one relatively deep, well-planned, expensive borehole which is likely to give representative and accurate information, may be more cost-effective than twenty seemingly inexpensive shallow ones in terms of predicting the geological and engineering problems of an area.

It is also apparent that there is still a yawning gap, albeit a little narrower than when the M6 was planned 20 years ago, between the outlook, training and experience of the engineer and the geologist. Each still needs to assimilate more of the theory and practice of the other, and this problem is enhanced as knowledge increases so rapidly. In the case of pebble beds the problems of exploring and exploiting the sandstones tend to hide these differences, those of the conglomerates to magnify them. Several geologists and engineers to whom first drafts of the previous paper (Buist & Thompson, 1982) were given for comment complained respectively that the technicalities of both the engineering techniques and the sedimentology were too great and they asked that the account should be simplified, and this was done. On the other hand a relatively youthful former student of the author, having taken a joint honours degree in geology and physics and subsequently having undergone the specialised training of an M.Sc. Engineering Geology course, called for the inclusion of much more detailed sedimentology, a greater discussion of the details of the techniques of site investigation and a whole section on the management skills appropriate to work on areas of the pebble beds. The author believes that both the geological and engineering professions should pay much more attention to the organisation of both the pre-service and in-service training of their personnel in interdisciplinary applied studies.

## Acknowledgements

The author is pleased to be able to record his thanks to Professor Emeritus S.H. Beaver (formerly Senior Geological Research Officer of the Ministry of Town and Country Planning, from 1943, and geologist to the Waters Committee from 1946 onwards), Mr. M. Rae, M.B.E. (formerly of Amey Roadstone Ltd.), and Dr. D.S Buist (formerly of the Department of Transport, Midland Road Construction Unit) for useful comments on early drafts of this paper. Thanks are also due to Doreen Thompson for secretarial work.

## References


ABERCROMBIE, P. & JACKSON, H. (Eds.) 1949. *North Staffordshire Plan.* Advanced Edition. London; Ministry of Town and Country Planning. 328pp.

BEAVER, S.H. 1949. *Physical Background and Natural Resources.* pp.73-114 in ABERCROMBIE, P. & JACKSON, H. (Eds.)

BEAVER, S.H. 1968. *The geology of sand and gravel.* London; Sand and Gravel Association. 66pp.

BLACK, G.P. 1978. *Geology in conservation.* Ch.13, pp.310-334 in KNILL, J.L. (Ed.)

BUIST, D. & THOMPSON, D.B. 1982. Sedimentology, Engineering Properties and Exploitation of the Pebble Beds in the Sherwood Sandstone Group (?Lower Triassic) of North Staffordshire with particular reference to highway schemes. *Mercian Geol.*, vol.8, no.4, pp.241-268.

DEPARTMENT OF TRANSPORT 1976. *Stoke-Derby Link. 'Your views are needed'.* Leamington Spa; Department of Transport. Midland Road Construction Unit. Broadsheet; no pagination.

KNILL, D.C. 1978. *Aggregates, sand, gravel and constructional stone.* Ch.8, pp.166-195, in KNILL, J.L. (Ed.). *Industrial Geology.* Oxford Univ. Press. 344pp.

MINISTRY OF HOUSING AND LOCAL GOVERNMENT 1950. *Report of the Advisory Committee on Sand and Gravel (The Waters Committee), Part 3: Trent Valley; Part 4; West Midlands.* London; HMSO, 81pp.

MINISTRY OF HOUSING AND LOCAL GOVERNMENT 1952. *Report of the Advisory Committee on Sand and Gravel (The Waters Committee), Part 10; North-West Gravel Region.* London; HMSO, 38pp.

RAE, R.M. 1976. *(Unpublished address to members of the Sand and Gravel Association)* Shrewsbury; Amey Roadstone Ltd., 7pp. (available from the present author upon request).

STAFFORDSHIRE COUNTY COUNCIL 1969. *Town and Country Planning Act 1962. County Development Review. Sand and Gravel; Report of Survey.* Stafford; Staffordshire County Council, 49pp.

STEEL, R.J. & THOMPSON, D.B. (In preparation.) Structure and texture in Triassic (?Scythian) braided stream conglomerates in the Pebble Beds of the Sherwood Sandstone Group in North Staffordshire, England.

VAIL, P.R., MITCHUM, Jr. R.M., TODD, R.G., WIDMIER, J.R., THOMPSON, S., SANGREE, J.B., BUBB, J.N. & HATFIELD, W.G. 1977. Seismic stratigraphy and global changes of sea level in PAYTON, C.E. (Ed.); Seismic stratigraphy, Application to Hydrocarbon Exploration. *Am. Assoc. Pet. Geol. Mem.*, vol.26, pp.42-212.

WARRINGTON, G., AUDLEY-CHARLES, M.G. ELLIOTT, R.E., EVANS, W.B., IVIMEY-COOK, H.C., KENT, P., ROBINSON, P.L., SHOTTON, F.W. & TAYLOR, F.M. 1980. A Correlation of Triassic rocks in the British Isles. *Geol. Soc. Lond.*, *Special Report*, No.13, 78pp.

WILLS, L.J. 1970. The Triassic succession in the Central Midlands in its regional setting. *Q. Jl. geol. Soc. Lond.*, vol.126, pp.225-85.

WILLS, L.J. 1976. The Trias of Worcestershire and Warwickshire. *Rep. Inst. Geol. Sci.*, No.76/2, 221pp.

ZIEGLER, P.A. 1981. *Evolution of Sedimentary Basins in North-West Europe.* pp.3-42 in ILLING, L.V. & HOBSON, G.D. *Petroleum Geology of the Continental Shelf of Northwest Europe.* London, Heyden & Son for the Institute of Petroleum, 521pp.

D.B. Thompson, B.A., M.Sc., F.G.S.,
Department of Education,
University of Keele,
Staffs. ST 5 5BG.

Postscript:

As this paper and the previous one (Buist & Thompson, 1982), have been prepared for publication the following have been published by the Institute of Geological Sciences (UK).

PIPER, D.P. 1981. The conglomerate resources of the Sherwood Sandstone Group of the country east of Stoke-on-Trent, Staffordshire. Resources sheet SJ94. *Mineral Assessment Report*, No.91, Institute of Geological Sciences, HMSO, London.

ROGERS, P.J., PIPER, D.P., & CHARSLEY, T.J. 1981. The conglomerates of the Sherwood Sandstone Group of the country around Cheadle, Staffordshire. Resources sheet SK04. *Mineral Assessment Report*, No.57. Institute of Geological Sciences, HMSO, London.

# THE SOUTH PENNINE OREFIELD:

# ITS GENETIC THEORIES AND EASTWARD EXTENSION

by

P.R. Ineson and T.D. Ford


## Summary

Genetic theories regarding the origin of the Pb-Zn-Ba-F mineralisation of the South Pennines generally invoke the leaching of at least some of the metals and anions by hypersaline brines from strata in adjacent sedimentary basins. The ores are emplaced in structural culminations (apparently controlled by basement tectonics) the basins adjacent to which expelled large quantities of deep formation waters. Depositional models are based on direct evidence from mineral occurrences in the exposed orefield and exploration boreholes in the concealed extension eastwards.

Genetical implications result from geophysical surveys of the surrounding basins, analyses of groundwaters, heat flow, isotopic studies, geochronology, trace element geochemistry, mineral zonation and fluid inclusion research, all seen in the context of the stratigraphical and structural setting of the South Pennines and surrounding areas.

Collation of all the available information leads to the conclusions that mineral fluids migrated from the east though the exact source(s) remain uncertain, and that deposits probably occur at depth beneath the Upper Carboniferous and younger strata of the East Midlands.


## Introduction

Comprehensive research on mineral zonation, structural and stratigraphical studies, fluid inclusion geothermometry, hydrogeochemistry, geophysical surveys, wallrock alteration, trace element geochemistry, isotopic analyses and geochronology has provided the evidence upon which the genetic models for the occurrence and migration of the ores and minerals located in the South Pennine (or Derbyshire) orefield, have been based.

The work has indicated that the South Pennine Orefield is the most complex of the three Pennine orefields. Unlike the Alston and Askrigg Orefields, the mineral zonation in the South Pennines is not concentric but aligned in a north-south direction on the eastern margin of the

Mercian Geologist, vol. 8, no. 4, 1982
pp. 285-303, 1 text-fig., 1 table.

Carboniferous Limestone massif. The fluid inclusion data has not yet delineated any significant 'hot spots'. Geophysical evidence has not defined more precise 'basement models'. Isotopic studies have indicated a high degree of intermixing of the ore fluids. The overall concensus of opinion, albeit based on incomplete evidence, was that the most probable source for the ore minerals or fluids was from the east with expulsion of formation waters from deep sedimentary basins.

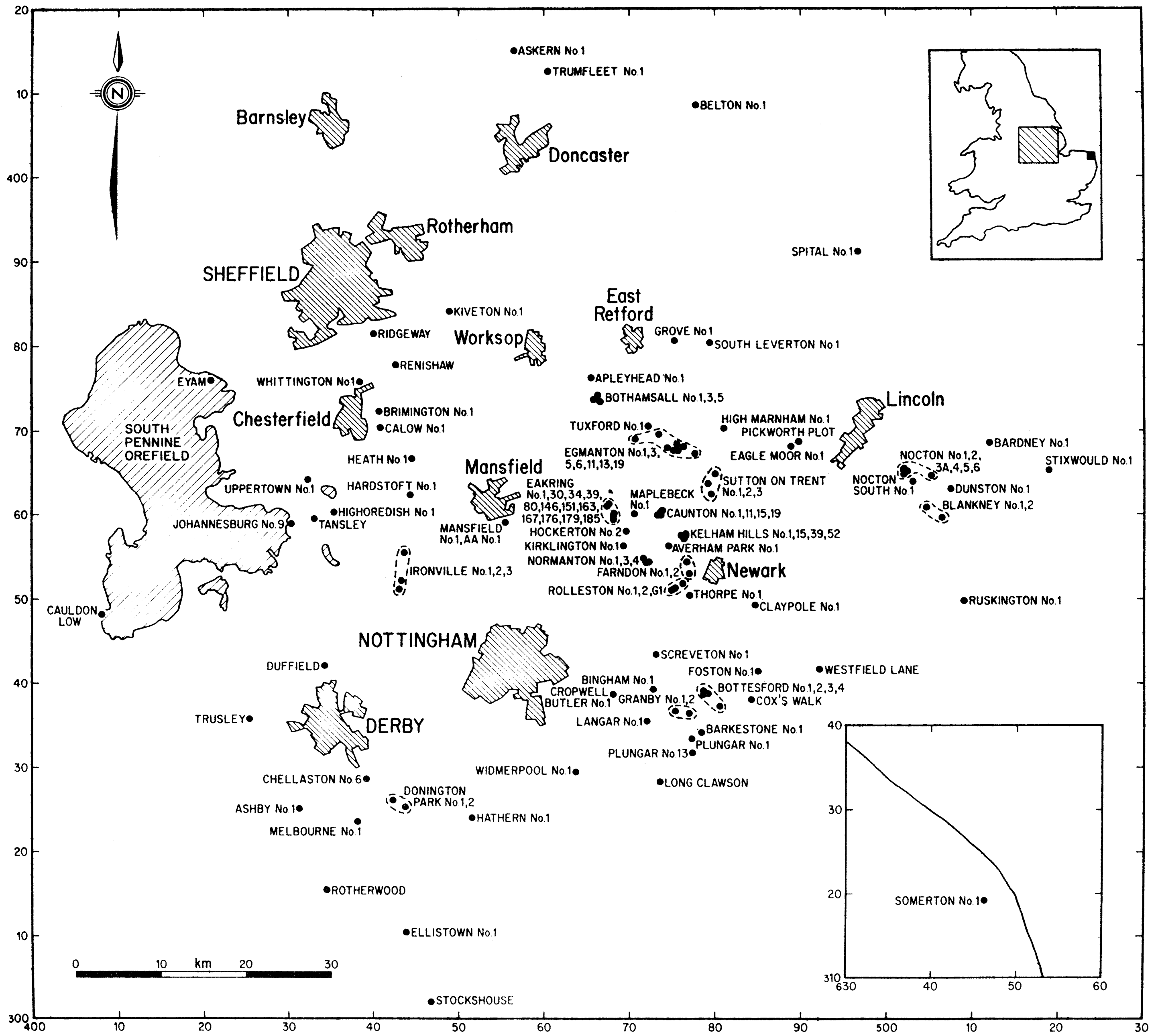
A study of areas peripheral to the South Pennine Orefield, has provided new evidence in support of this genetic hypothesis, which has not been available elsewhere in the Pennines. This is due to geological exploration for fossil fuels in the East Midlands, the initial results of which have been presented by Lees & Kent (1960) and Kent (1966, 1967, 1968). More than a hundred deep boreholes (see table 1, p. 296-297, and text-fig. 1) combined with geophysical surveys have indicated Carboniferous and pre-Carboniferous structures, and several boreholes have penetrated into the Precambrian or Lower Palaeozoic basement. In the search for oil, discoveries have been made of base metal mineralization in Dinantian limestones. The authors herein show that not only were the small oilfields located over basement highs, but demonstrate that the base metal mineralisation may likewise be located on the flanks and above such structures.

## The Genetic Models

In describing the distribution of fluorite, Wedd & Drabble (1908) advocated the lateral up-dip movement from the east of the mineralising fluids within the strata between the impermeable layers of lavas, tuffs, etc. Schnellmann & Willson (1947) suggested that the main feeders were concentrated along the eastern margin of the exposed limestone, whilst Dunham (1952), drawing an analogy with the Northern Pennines, stated that the fluorite zone lay nearest to the source of the fluids, which he then envisaged to be of granitic nature. Following Dunham's lead, Ford (1961) similarly suggested a granitic source for the South Pennine mineral solutions "near or under the eastern margins of Derbyshire".

At that time, what appeared to be a most controversial hypothesis was proposed by Davidson (1966) who suggested that the ores were deposited by interstratal brines, derived diagenetically from evaporites, leaching and concentrating the metals from the sediments through which they migrated. Precipitation occurred when the fluids mixed with later diagenetic brines enriched with sulphate and bacteriogenic sulphide. This hypothesis was countered by Dunham (1966) who suggested that the evaporitic source - the Upper Permian Zechstein dolomites and evaporites - had been insulated from the mineralised sediments by impervious Upper Carboniferous shales. If the preliminary fluid inclusion data were to be believed it implied burial of the source sediments to a depth of some 15 km. As Dunham noted, arguments for or against the direct genetic connection with evaporitic sequences were equivocal, but he did accept that the evaporites could provide additional chlorine and/or potassium in the brines, as noted by fluid inclusion studies. Substantiating evidence was subsequently provided by Downing (1967) who reported that the Na and Ca chlorides predominate in the down-dip groundwaters of the Carboniferous Limestone in east Derbyshire and adjoining counties. He also noted that a belt of sulphate-rich groundwaters appeared to coincide with a depression in the sub-Carboniferous floor. This latter statement, although at the time being of relatively minor significance, was to provide evidence for theories then in the initial stages of formulation.

Although the Pennine Orefields have been cited (Ford, 1976) as an example of 'Mississippi Valley type' mineralisation, and models for these types of deposits (Beales & Jackson, 1966; White, 1968; Dozy, 1970; Beales & Onasick, 1970) may be used in more generalised genetic models even this approach has been questioned by Worley & Ford (1977) and Emblin (1978). These last two compilations must therefore be viewed in the light of Dunham's (1966) suggestion that the derivation of some of the ore minerals may have been by the lateral secretion of elements from micas in the basement. At approximately the same time King (1966) concluded that while the rakes in Derbyshire were of a plutonic-hydrothermal origin, some pipe deposits were neo-Neptunist, and other ore-bodies may have had a varied origin.




Text-fig. 1: Geographical location of boreholes in the East Midlands which have penetrated the Carboniferous (Dinantian) Limestone or basement formations.

In reviewing the mining potential of the South Pennines, Ford & Ineson (1971) concluded that future exploration and development should investigate faults and anticlinal structures in the Carboniferous Limestone beneath the Upper Carboniferous cover east of the orefield. This suggestion was based on Dean's (1961) description of stratiform deposits in the Permian Magnesian Limestone of Nottinghamshire, and King's (1966) diagnosis of episyngenetic deposits, as well as the report of a near-surface barite-galena vein in the Upper Magnesian Limestone (Ineson *et al.*, 1972). In this paper it was suggested that the genesis of the Permo-Triassic deposits and those in the Carboniferous Limestone were closely related in that they may be fault-controlled with the intermixing of juvenile and connate waters from the deep sedimentary basins beneath the general area of the East Midlands. As the mineral assemblage in the Permo-Trias is similar to that of the outer (calcite) zone in the South Pennine Orefield, these occurrences may be classed as leakage deposits overlying a steeply dipping eastern extension of the orefield.

In order to investigate the stratigraphical succession and prove the true nature of the basement beneath the South Pennine Orefield, the Institute of Geological Sciences sank a deep borehole near Eyam (see table 1). The preliminary results were reported by Dunham (1973) who described equivalents of the exposed Viséan succession resting on a previously unrecognised and unexpectedly thick Tournaisian limestone sequence with basal anhydrites; he suggested that the mineralisation might be concentrated on the flanks of basement highs in proximity to basins from which large quantities of deep formation waters were expelled.

In 1976, Ford reviewed the ore genesis of the South Pennine Orefield and argued that the ore fluids were derived from strata beneath the North Sea basin and the fluids slowly diffused through the Carboniferous Limestone towards the basin margin in the Pennines. The sulphurous hydrocarbons (Mueller, 1954b; Pering, 1973), disseminated pyrite and the basinal limestones together with the bacterial reduction of the Tournaisian anhydrite sequences (see Dunham, 1973) were all invoked as possible sources for sulphur. Since the anhydrites are still in place, they could only have been a minor source of sulphate fluids, though it was thought possible that the limestone formation waters could have been sulphate-rich if evaporite interludes in sedimentation had only approached, but not reached, the concentrations necessary for sulphate precipitation. The isolated mineral occurrences peripheral to the South Pennines were considered (Ford & King, 1968) to represent partially depleted mineralizing solutions leaking to the surface as hot springs or into the Triassic groundwater circulatory system.

Evans & Maroof (1976), using an analogy with Bott's interpretation of basement structures, suggested that the East Midlands basement intrusions may have directed mineralising solutions into the anticlinal areas. They also stated that the mantle must be considered seriously as a possible source rock.

As fluid intrusion studies had provided useful evidence in the Alston Block, so it was argued should similar studies on the Derbyshire material (i.e. fluorite). Results reported by Smith (1973), Ford (1976) and Rogers (1977) provided only an outline picture and additional work on *in situ* material is being undertaken at present.

In an attempt to clarify the origin, intermixing and depositional history of the ore fluids, the analysis of sulphur, oxygen and carbon isotopes was undertaken by Robinson & Ineson (1979) in the South Pennines who reported that analyses of barite, calcite, galena and sphalerite showed unique trends and reflected a high degree of mixing of fluids and components from many different sources. Barite results, for example, were explained by the partial mixing of fresh-water sulphate and connate sea-water sulphate. The reduced sulphur may have had a dual source, one part being derived from biogenic sulphur in the limestone kerogens (light sulphur) and the other source (heavy sulphur) resulting from the reduction of connate sea-water sulphate. The deposits fitted a pattern of brines, of either sabkha or connate origin that were interpreted as being derived from the east. As they moved into the limestones and encountered initially reducing fluids, they gave rise to the precipitation of sulphides.

In a Yorkshire Geological Society symposium on the sub-Carboniferous basement in Northern England, Bott (1967) described the configuration of the underlying Devonian granites beneath the Alston and Askrigg Blocks as well as concluding that the primary mineralising fluids had risen through the granites. Kent (1967) implied that the NE Midlands were underlain by a NW-SE basement block and hinted that this may have genetic conotations, whilst Dunham (1967) stated that the solutions could not have a total primary connate origin and concluded that there was, at the time, no alternative but to propose rising hydrothermal waters with deep-seated magmatism beneath the Pennines emitting potassic brines with metals, or that the magmatism had stimulated the circulation of such solvents.

In reviewing the possible modes of mineralisation by deep formation waters, Dunham (1970) commented that large scale sedimentary basins "may prove to be the sources of some classes of epigenetic ore deposits". He also summarised the various research aspects needed to substantiate additional conclusions, and fortuitously Dunham's contribution was followed by Bush (1970) who suggested that chloride-rich brines derived from sabkha sediments might play an important role in ore formation. Although Bush quoted evidence and examples from the Trucial Coast of the Persian Gulf, he could well have chosen the Hathern Anhydrites, as Llewellyn and Stabbins (1968, 1970) did, to illustrate his theory. The latter authors suggested a link between the epigenetic mineralisation of the East Midlands and saline waters derived from anhydrite sequences.

The application of K-Ar isotopic geochronology as well as paragenetic studies on the ores, enabled Ineson & Mitchell (1972) and Ineson & Al-Kufaishi (1970) to conclude that the mineralisation was episodic and spanned a time interval from the Upper Carboniferous to the Jurassic, they were also able to recognise multi-phase injections of the same mineral suite. Dunham in 1970 stated that "it is apparent that multiple hypotheses leading to similar end products are no more avoidable here than elsewhere in geology: the intervention of igneous activity may or may not be a prerequisite; the water may originate in the ocean or as meteoric waters .... the deep sedimentary basins and their margins should receive more attention from the ore geologists".

Although the initial work on model lead isotopic ages (Moorbath, 1962) had reviewed the age of United Kingdom galenas, Mitchell & Krouse (1971), working in the Askrigg Block, reported anomalous J-type lead. The results were in keeping with models that either indicated mineral fluids of a deep-seated origin, released through fracturing during the Armorican orogeny, or that mineralisation may have been related to rheomorphism of the lower crust and leaching during those movements. A similar study on the South Pennines by Coomer & Ford (1975) also reported J-type leads emplaced in Carboniferous and Triassic strata.

One of the main differences between the South and North Pennine Orefields is that the former appears not be be underlain by granites, although Le Bas (1972) proposed that granites of a similar density to basement sediments may occur further east beneath the East Midlands. The available evidence (e.g. White, 1948, and the Institute of Geological Sciences, aeromagnetic map, 1965) enabled Evans & Maroof (1976) to suggest that competent basement rocks fractured and produced channelways for uprising solutions which, on reaching the overlying limestones, precipitated the metals and gave rise to mineralisation.

This could, in part, explain the absence of a concentric thermal zonal arrangement of the minerals. The orefield does display a mineral zonation though Stevenson & Gaunt (1971) commented that the zones of Wedd & Drabble (1908), Dunham (1952) and Mueller (1951 and 1954a) are only of general validity, as many anomalies and reversals in the zonation pattern are apparent. A survey of the distribution of non-metallic gangue minerals by Firman & Bagshaw (1974) demonstrated that, whilst stratigraphical, lithological and structural controls on deposition were important, episodic emplacement was fundamental in explaining mineral zonation. They agreed that the main supply of mineralising fluids was up the crests of plunging folds or along faults but suggested that locally the fluids migrated down-dip through more porous and cavernous strata, particularly if the faults threw impervious rocks against pervious, so creating hydrological barriers.

One of the more recent reviews of the literature has been by Emblin (1978) who proposed a compound sedimentary-diagenetic model for the Pennine Orefields in which fluid mobilisation and eventual orebody emplacement was ascribed to tectonic activity.

The majority of the authors who have theorised on the origin of the South Pennine Orefield have advocated, albeit with minor or major variations, transport from the east towards the west. The field evidence as well as the applied studies (e.g. isotopic and fluid inclusion data) would give credance to this general pattern of movement. Nevertheless, there is a strong possibility that the ores on the western flank, especially the copper ores at Ecton and Mixon in Staffordshire, may have originated from fluids migrating from west to east, i.e. out of the Cheshire basin, some of which leaked up faults to give the copper deposits in the Triassic sandstones of Alderley Edge (Carlon, 1979). Indeed Mueller (1954), Schnellmann (1955), Firman & Bagshaw (1974) suggested this while Robinson & Ineson (1979) provided isotopic evidence that a proportion of the mineralisation could only have been derived from the west. However, in the light of all the evidence it must be concluded that at present a major proportion of the mineralising fluids, emanated from a source, or sources, in the east.

Smith's (1974) work on the trace elements in Pennine fluorites showed the paucity of yttrium together with the comparative lack of fluorescence and indicated a major difference between the deposits in the south and the north. Furthermore, Russell (1976, 1978) related the ore deposits to plate tectonic models and alkali magmatism; however, at present there is no evidence to support or refute this hypothesis.

## South Pennine Orefield - concealed extensions

### Direct evidence

The most commonly quoted example of mineralisation beneath the East Midlands is the calcite-fluorite-barite veins intersected by the Eakring (Duke's Wood) No. 146 Borehole, (see table 1, text-fig. 1). This borehole and others sunk for oil exploration (Lees & Taitt, 1946) encountered mineralized ground characterized by the presence of silicification, brecciation and dolomitization of the Dinantian limestones. Other boreholes described by Gifford (1923), Boulton (1934), Lees & Tait (1946), Mitchell & Stubblefield (1948), Eden *et al.*, (1957), Falcon & Kent (1960), Ramsbottom *et al.* (1962), Kent (1966/67), Smith *et al.* (1967), Edwards (1967), Smith *et al.* (1973), Dunham (1973), Institute of Geological Sciences (1978), Frost & Smart (1979), B.P. & Conoco (pers. comm.) have continued to provide corroboratory evidence that: (a) veins, stratified or stratabound, and disseminated base metal mineralisation with the attendant gangue minerals and metasomatic alteration products, occur widely under the East Midlands; (b) saline waters are circulating in the strata; (c) gypsum or anhydrite-rich beds, etc. are locally present in Carboniferous strata; (d) flanking the South Pennines, deep Carboniferous sedimentary basins occur and (e) associated structural highs related to the basement appear to be the most favourable sites for the location of the base metals. Indeed, in the discussion of Schnellmann's paper (1955), it was even recorded that a 1 in 4, 914 m long cross-measure drift from Bilsthorpe Colliery, in the adjacent downwarp, could well have explored or even exploited the ground intersected by Eakring's No. 146 Borehole, beneath the oil-bearing Upper Carboniferous.

Using the data presented in text-fig. 1 and table 1 it is clearly possible to argue a case for the South Pennine Orefield being only the exposed part of a much larger mineral field, the majority of which is concealed beneath the East Midlands. The evidence is entirely from boreholes which have been sited on or close to structural highs determined by geophysical surveys, published summaries of which have been included in Lees & Taitt (1946), and Kent (1966 and 1967). These structures are the result of several phases of folding so that it should be possible to extract a regional slope of the top of the Carboniferous Limestone by a computer analysis of the heights of that formation in the boreholes (text-fig. 2). However, if one does the comparable exercise of regenerating a contour plot of the present topography from the collar heights of the boreholes it bears little resemblance to the observed topography, so that considerable caution should be used in interpreting the Carboniferous Limestone surface. After all, few boreholes are sunk in structural lows. Geophysical evidence for the form of the sub-Carboniferous basement is less accurate than could be desired, though it must be expected that the features of the basement will follow the pattern proved elsewhere in the world where both limestone sedimentation and structural configuration reflect basement culminations and depressions (e.g. Heyl, 1967; Ohle, 1967).

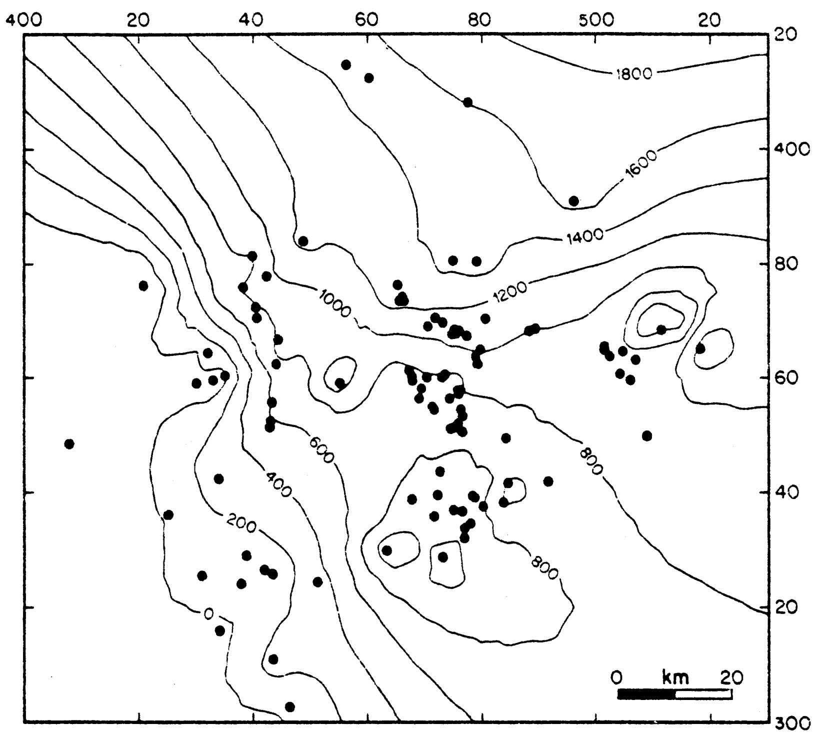
Indirect evidence

Considering the number of boreholes centred on or in the flanks of domal structures in the East Midlands (see table 1) it may be fortuitous that they have intersected mineralisation. A borehole located only a few metres either side of a deposit can visually fail to indicate that occurrence, though analyses indicate metasomatic alteration. Silicification and dolomitisation have been considered to indicate 'low temperature metasomatism by hydrothermal fluids' (see Frost & Smart, 1979, p. 12) but these conclusions cannot always be attributed to the proximity of mineralisation, and should not be taken as such when observed in borehole logs (see table 1). Furthermore thermal waters do not prove the presence of magmatic or other deep-seated fluids, for Edmunds' results (1971) showed that the geochemical analyses of such waters in Derbyshire are indicative of deeply circulating local meteoric waters.

The results of Downing (1967) and Downing & Howitt (1969) are more informative with respect to the potential 'carrying capacity' and when combined with the publications of Llewellyn & Stabbin (1968) on the presence of potential source rocks for the alkali chlorides, and Lees & Taitt (1946) and Kent's (1966, 1967) structural information, they support Dunham's (1973) proposal for derivation from the flanks of basement highs and deposition in domal areas (Shirley & Horsfield, 1945; Shirley, 1959, p. 420).

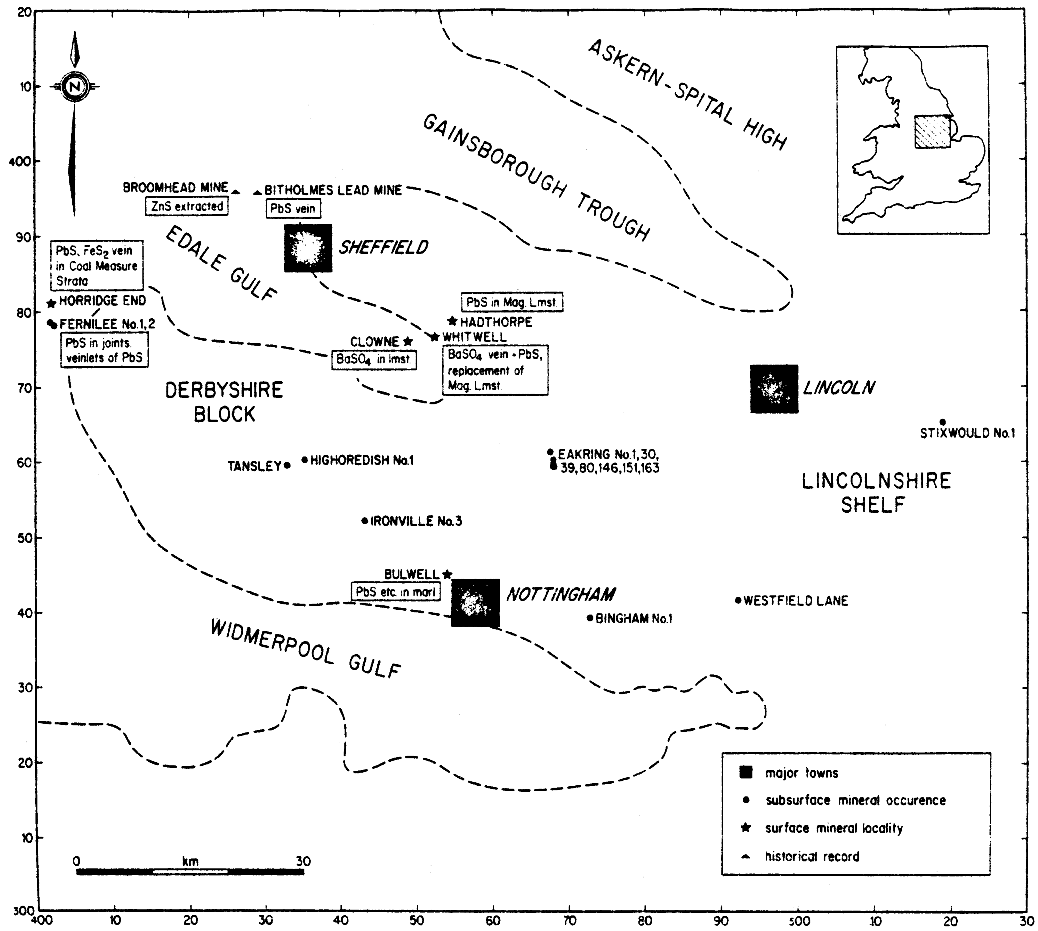
Ford (1976) proposed that a possible derivation of the metals was from the North Sea basin. This hypothesis, as Robinson & Ineson (1979) indicated, required a transport flow over a distance of at least 160 km. They noted the presence of the Gainsborough, Edale and Widmerpool Gulfs separating a Lincolnshire shelf area and the Askern-Spital high (Kent, 1966, 1967) and suggested that the gulfs may have acted as barriers to the westerly migration of the magnitude by Ford, and hence the basinal sediments in the gulfs could then have been the sources of the metals (see text-fig. 3). However, recent information supplied by Conoco does tentatively support Ford, in that the Somerton Borehole on the Norfolk coast (see table 1) encountered mineralised ground in the Carboniferous Limestone at a depth of over 1000 m.

Kent (1966 and pers. comm.) noted a westward pre-Permian stratigraphical gradient (i.e. rate of increase of thickness as measured in the Coal Measures, probably also present in the Carboniferous Limestone) into the Pennine sedimentary basin. Thus, during Carboniferous times migration of fluids would have been eastwards towards the basin margin, though doubtless meeting greater quantities of fluids migrating westwards out of the North Sea basin somewhere under the East Midlands or near the coast. By the end of the Carboniferous the structural uplift of the Pennines reversed the gradient and from Permian times onwards long distance fluid migration from east to west could much more easily have been established. The effects of the Gainsborough, Edale and Widmerpool Gulfs and any eastwards extensions would be to provide local sources of fluids during the Carboniferous, while the intervening highs provided traps then and later. Kent believes that the relative richness of hydrocarbons at Eakring and Gainsborough in part relates to eastwards migration out of the Pennine basin, perhaps guided by the arrangement of gulfs and platforms. The reversal of gradient at the end of the Carboniferous caused by the Armorican movements offers a possible explanation for the dual source for mineralising fluids proposed on isotopic arguments by Robinson & Ineson (1980), and for the major episodes of emplacement deduced from K-Ar dates by Ineson & Mitchell (1972). Broadly a late Carboniferous episode could have been derived largely from the Pennine basin, with some mixing of North Sea fluids, while later episodes were dominated by North Sea fluids mixed with residual Pennine fluids. If paragenetic studies could show which parts of the exposed mineral field were of late Carboniferous age and which were later, a much stronger case could be put forward for this hypothesis, but too little paragenetic research has been carried out so far.




Text-fig. 2: Computer generated contour plot of the top of the Carboniferous Limestone (depths below O.D. in metres).

Boreholes used in computer program.




Text-fig. 3: East Midlands Carboniferous blocks and gulfs, after Howitt & Brunstrom (1966) with the addition of mineral localities both at surface and in boreholes.

Fluid inclusion studies might demonstrate a thermal gradient if they could be related to the episodes of mineralisation. However, the results from Eakring (Rogers, 1977) indicate a homogenisation temperature range of 86-98° C. (mean 92.4° C.) and when compared with the results for the South Pennine Orefield (range 92-154° C, + 11° C. as a pressure correction) neither area is shown to have an anomalously high formational temperature and no gradient can be demonstrated in either direction.

An easterly heat-flow gradient was noted in the Eakring area as early as 1951 (Bullard & Niblett, 1951) though this area lies in the middle of the high heat-flow belt demonstrated more recently by Brown *et al.* (1980). They showed that there was a broad northwest to southeast high heat-flow belt across the Pennines, with the South Pennine Orefield on its western margin. Brown *et al.* argued that this belt is possibly due to heat-generating radioactive minerals in concealed Caledonian granites and that such a heat-flow gradient falling from east to west has existed since emplacement of the granites. Such a gradient supports the concept of westwards movement of ore-fluids into the exposed orefield but Brown *et al.* suggest the granites may lie beneath highs in eastern and northeastern England, possibly enhancing the dual source effect of the basins in the Carboniferous and the barrier effect later.

Iron sulphides and organic compounds (kerogens and other hydrocarbons) are usually concentrated in black shales deposited under euxininc conditions and, as Dunham (1961) indicated "... while a concentration of trace amounts of other metals may have been achieved in ancient black muds, high concentration of such metals as copper, zinc and lead was only produced where very special local circumstances prevailed. The special circumstance favoured in this paper is the operation of submarine springs, releasing juvenile or hydrothermal fluids into a stagnant environment ...". A subsequent publication by Hirst & Dunham (1963) on the Permian Marl Slate in southeast Durham, proposed that the origin of Zr, Sr, Rb, Mo, Co, Ni and Mn ± Cu in the Marl Slate may have been the result of normal weathering. The source for the enhanced Pb, Zn and Ba ± Cu may be due to (a) the weathering of exposed mineral veins from the Alston area, (b) post-consolidation via hydrothermal solutions, or (c) by introduction via submarine springs into the lagoon. They favoured the last hypothesis.

Recent work by Spears & Amin (1981) on the marine and non-marine Namurian black shales from the Tansley Borehole (see table 1) has provided direct evidence that at least during or subsequent to the diagenesis of the Namurian, the marine black shales have accumulated enhanced quantities of Pb, Cu, V and Ni with respect to the non-marine shales. Interpreting these results in the light of Hirst & Dunham's findings it may be argued that enhancement of V, Ni + Cu may be the result of surface weathering, but not Pb. Spears & Amin report an average content in the non-marine shales of 37 ± 16 ppm Pb, whilst the marine shales have 155 ± 44 ppm Pb indicating a 319% increase between these horizons. When these figures are compared with average (median of the medians of 20 sets) world black shales (Vine & Tourtelot, 1970; Holland, 1979) which contain 20 ppm, the marine shales in the Tansley Borehole are significantly anomalous ($90^{th}$ percentile for the 20 sets = 70 ppm).

Spears & Amin (1981) relate these enrichments to reactions involving organic matter and oxyhydroxide material in environments in which salinity and slow rate of sedimentation were important factors. However, they state that the results cannot be related directly to seawater concentrations as often has been the case for black shales. The origin of these extremely low concentrations is unknown but may be related to diagenetic processes.

The sporadic mineral deposits in the Permo-Triassic of eastern England may be related to mineralisation. Possibly one of the most well known deposits in the galena-wulfenite-uraniferous-asphaltite horizon in the Magnesian Limestone of Nottinghamshire (Deans, 1961), although other deposits, either vein, stratabound/stratified, replacement or discrete masses have been recorded by King (1966), Ford & King (1968), Ineson *et al.* (1972), Taylor & Holdsworth (1973), Hirst & Smith (1974) and Carlon (1979). These deposits may be classed as 'leakage deposits' whose migratory channelways were faults connecting with the underlying Carboniferous strata, and the subsequent deposition in the next overlying suitable host rock - the Magnesian Limestone or higher porous sandstones. However, Deans stated that they may have resulted from re-deposition of syngenetic ores precipitated in certain phases of Zechstein sedimentation and remobilised during the complex dolomitisation process. Hirst & Smith (1974) showed that barite mineralisation to the east of the Alston Block corresponds closely to structurally positive features and the precipitation of the barite is attributable to the mixing of $BaCl_2$-bearing brines, derived from the Coal Measures, with $SO_4^{2-}$-bearing brines from the Permian. By contrast they were unable to deduce an origin for the attendant fluorite except to state that it appeared to be unrelated to the economically exploitable deposits in the Alston Block.

The data presented in the text-fig. 1 and table 1 include all the non-confidential records of boreholes which have reached the Carboniferous Limestone, but few of these have recorded mineralisation, perhaps because at the time of drilling it was of little interest to the oil companies. In the future, however, it would help to substantiate the hypothesis presented herein of a concealed ore-field if all boreholes could have any attendant mineralisation recorded. Furthermore, the cores could be studied for trace-element chemistry of the ore minerals and their associates. Whilst the Namurian and Westphalian are known to contain non-economic quantities of the ore minerals, and some trace element studies have been conducted, no systematic survey of these formations has been conducted from a ore-genesis concept point of view. Senior Geologists of the National Coal Board have commented "it is mainly the lithological units we are primarily interested in and, consequently we do not give an 'in depth' description of any mineralisation that occurs". However, there are records of mineralised faults as well as discrete sporadic occurrences but no true metalliferous deposits. For example, in the Roall borehole, southwest of Selby it was noted "joint with small displacement and calcite mineralisation, dip 45°". Mr. R.W. Vernon related "we find sporadic traces of barytes, and calcite with pyrite in Permian Limestone and Coal Measures adjacent to and in fault zones. Very rarely do we see traces of galena". Likewise, Mr. D.E. Raisbeck stated "We have a record, and a sample exists at the colliery, of a small trace of galena on a fault plane in the Elmton Trough fault at Cresswell Colliery, Nottinghamshire. The depth would be approximately 540 m, below O.D. in the Three-quarter Seam. There is a record of barytes and galena at a depth of 213 m (some 9 m above the Wales coal) in Buskeyfield Lane, National Coal Board borehole (E.456, 171 m, N.371, 988 m)".

A visit to almost any colliery in the Pennines will produce reports of 'brass' (= pyrite) and lead (presumably galena) etc. having been found in the workings. Some of this is probably diagenetic but without a systematic survey both in the field and geochemically, the significance of the Upper Carboniferous both as a depositional site and as a potential source of ore-fluids must remain unknown.

## Conclusions

The genesis of the South Pennine Orefield is related to the up-dip migration in a westerly direction of thermally elevated metal-leaching hypersaline brines at least since the end of the Carboniferous. Emplacement in the ground beneath Lincolnshire, Nottinghamshire, East Derbyshire and possibly north Leicestershire and North Norfolk has been on the fold culminations and on their flanks, within the most favourable host rock - the Carboniferous Limestone. These anticlinal structures may tentatively be related to similar but as yet unproved culminations in the pre-Carboniferous basement.

The mineral fluids in which meteoric and connate waters pre-dominate over juvenile waters have been expelled during Upper Carboniferous to Lower Jurassic times and in fact may still be being released from deep sedimentary basins to the east beneath the North Sea. Minor and more localised components may have been provided by the sedimentary downwarps of the Carboniferous Pennine basin, and the gulfs indenting the Lincolnshire shelf.

Of an unknown initial composition, the fluids later became hypersaline in composition. The depth of initial mobilisation depended on the contemporary geothermal gradient, possibly affected by magmatic influences, but it was more than adequate to elevate these fluids to the depositional temperatures now recorded in the orefield, even allowing for some heat-loss during migration.

TABLE 1

Borehole Information on the Dinantian Limestones to East of the South Pennine Orefield

| Borehole Name and Number | | Source of Information | Locality (National Grid Reference) * Computer Generated | Collar or KB Height (m) | Dinantian Limestone Depth to: Top (m) | Dinantian Limestone Depth to: Base (m) | Total Depth of Borehole (m) | Dinantian Zone | Mineralisation and Other Details | Overlain by: | Underlain by: |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Apleyhead | No.1 | J | SK 65510.76310 | 43.89 | 1399.03 | | 1467.00 | D,P? | Calcite Veins | Namurian ($E_1$) | ? |
| Ashby | G1 | D,O,P | SK 31340.25240 | 59.40 | ·284.07 | | 285.90 | $C_2S_1$,$D_1$-$P_{1a}$ | | Namurian | ? |
| Askern | No.1 | F | *SE 56526.15027 | 7.62 | 1452.98 | | 1467.00 | | | Namurian | ? |
| Averham Park | G1 | C,F | SK 74505,56305 | 48.77 | 800.10 | | 805.89 | | Strong Brecciation | Namurian | ? |
| Bardney | No.1 | G,O,P | TF 11915.68617 | 5.79 | 5.72 | 1851.05 | 1897.99 | | Dolomitisation | Namurian | Cambrian ? |
| Barkestone | No.1 | C | *SK 78348.34261 | 60.05 | 944.27 | | 1005.84 | | | Namurian | ? |
| Belton | No.1 | F,O,P | SE 77730.08450 | 4.72 | 1610.87 | | 1663.90 | | | Namurian | ? |
| Bingham | No.1 | O,P | SK 72520.39350 | 26.59 | 873.86 | | 1814.7 | | Galena,calcite veins. | Namurian | ? |
| Blankney | No.1 | C | *TF 06398.59698 | 28.35 | 907.99 | | 940.31 | | Oil in Limestone | Namurian | ? |
| Blankney | No.2 | C | *TF 04565.60854 | 38.40 | 932.69 | | 936.96 | | | Namurian | ? |
| Bothamsall | No.1 | I,P | SK 65860.73675 | 35.74 | 1367.64 | | 1427.68 | $D_2$,$P_2$? | Pyrite,bituminous | Namurian | ? |
| Bothamsall | No.3 | J | SK 66320.74210 | 34.44 | 1342.64 | | 1432.56 | $D_2$,$P_2$ | Pyrite in limestone | Namurian | ? |
| Bothamsall | No.5 | I,P | SK 66595.73440 | 37.72 | 1365.20 | | 1388.97 | | Pyrite in limestone | Namurian | ? |
| Bottesford | No.1 | C | *SK 79095.38853 | 30.78 | 975.36 | | 988.47 | | | Namurian | ? |
| Bottesford | No.2 | C | *SK 80437.37401 | 40.54 | 963.17 | | 973.23 | | | Namurian | ? |
| Bottesford | No.3 | C | *SK 78610.39194 | 28.04 | 990.90 | | 994.26 | | | Namurian | ? |
| Bottesford | No.4 | F,P | *SK 78581.38804 | 31.69 | 983.28 | | 995.48 | | | Namurian | ? |
| Brimington | | H | SK 40720.72310 | 135.94 | 915.92 | | 1231.39 | | Anhydrite and Toadstones | Namurian | ? |
| Cauldon Low | | L,P | SK 08040.48220 | 335.00 | 000.00 | | 535.37 | $C_1$,$C_2$? | Dolomitisation | Namurian | ? |
| Calow | No.1 | H | SK 40860.70410 | 128.01 | 830.27 | | 1132.94 | D,$D_2$?,$P_2$ | Cherts, toadstones, tuffs, etc. | Namurian ($E_1$) | ? |
| Caunton | No.1 | I,P | SK 73790.60570 | 39.32 | 787.91 | | 818.69 | Viséan? | Brecciated limestones | Namurian | ? |
| Caunton | No.11 | I,P | SK 73520.60310 | 30.18 | 758.34 | | 768.71 | | | Namurian | ? |
| Caunton | No.15 | I,P | SK 73600.60000 | 33.83 | 753.77 | | 768.10 | | | Namurian | ? |
| Caunton | No.19 | I,P | SK 73250.60000 | 51.21 | 791.87 | | 794.92 | | | Namurian | ? |
| Chellaston | No.6 | D,O,P | SK 39220.28710 | 42.10 | 117.35 | | 151.79 | $P_1$ | | Namurian | ? |
| Claypole | No.1 | C | SK 84501.49332 | 17.68 | 621.18 | | 669.34 | | | Namurian | ? |
| Cox's Walk | | R | SK 84115.38077 | 56.00 | 499.70 | 566.20 | 800.60 | Asbian/Holkerian | Dolomite | Namurian | Charnian(Maplewell Series) |
| Cropwell Butler | No.1 | O,P | SK 68135.38695 | 63.66 | 962.25 | | 980.54 | | | Namurian | ? |
| Donington Park | No.1 | D,O | SK 42330.26240 | 70.10 | 76.40 | | 93.40 | $P_1$ | | Widmerpool Formation | ? |
| Donington Park | No.3 | D,O | SK 43760.25450 | 85.30 | 55.90 | | 84.10 | | | Namurian | ? |
| Duffield | | M | SK 34280.42170 | 61.57 | 417.88 | | 1052.47 | $P_1$,$P_2$ | Faults, tuffs, dolerite sills | Namurian ($E_{1a}$) | ? |
| Dunston | No.1 | C | *TF 07399.63124 | 12.50 | 1290.52 | | 1299.97 | $D_2$ | Penecontemporaneous brecciation | Namurian | ? |
| Eagle Moor | No.1 | F | *SK 88747.68203 | 31.69 | 1029.00 | | 1041.81 | $D_1$ | | Namurian | ? |
| Eakring | No.1 | I | SK 67600.61330 | 90.83 | 805.59 | | 819.91 | | Veins + cav. $CaF_2$,ZnS,PbS,$BaSO_4$ | Namurian | ? |
| Eakring | No.30 | I,P | SK 68170.60210 | 118.26 | 812.90 | | 824.48 | | Pyrite and phosphate nodules | Namurian | ? |
| Eakring | No.34 | I,P | SK 68050.59870 | 116.13 | 786.38 | | 803.45 | | | Namurian | |
| Eakring | No.39 | I,P | SK 68200.59620 | 103.02 | 787.60 | | 800.05 | | Silicified + veins of $CaF_2$,$BaSO_4$ | Namurian | ? |
| Eakring | No.80 | I,P | SK 68050.59380 | 99.36 | 784.86 | | 803.76 | P? | Veins of $CaCO_3$,$SiO_2$,$BaSO_4$,$CaF_2$ | Namurian | ? |
| Eakring | No.146 | I,P | SK 68075.59450 | 104.24 | 778.76 | 2209.80 | 2278.68 | Brigantian/Courceyan | Veins-$CaF_2$,$BaSO_4$,$CaCO_3$,ZnS,$SiO_2$+ elaterite | Namurian cemented by $CaF_2$, $SiO_2$ | Cambrian |
| Eakring | No.151 | I,P | SK 68170.59370 | 101. 0 | 797.97 | | 813.82 | P? | Veins-PbS,ZnS,$CaF_2$,$BaSO_4$ + hatchettite | | |
| Eakring | No.163 | I,P | SK 68030.59740 | 103.63 | 785.47 | | 800.10 | | Veins-$CaCO_3$ and pyrite | Namurian | ? |
| Eakring | No.167 | I,P | SK 68180.59730 | 107.89 | 794.00 | | 805.59 | | Quartz Grit, $CaCO_3$ veins, | Namurian | ? |
| Eakring | No.176 | I,P | SK 67970.59560 | 94.79 | 763.22 | | 786.38 | | Quartz grit, siliceous limestone | Namurian | ? |
| Eakring | No.179 | I,P | SK 67490.61220 | 98.45 | 801.01 | | 817.47 | | Brecciated limestone | Namurian | ? |
| Eakring | No.185 | I,P | SK 68080.59530 | 104.54 | 783.64 | | 807.72 | | Quartzitic | Namurian | ? |
| Egmanton | No.1 | I,F | SK 75510.68420 | 34.44 | ~1146.96 | | 1205.18 | Visean($P_2$?) | | Namurian | ? |
| Egmanton | No.3 | I | SK 77570.67330 | 21.34 | ~1103.07 | | 1121.36 | | | Namurian | ? |
| Egmanton | No.5 | I,P | SK 76260.68130 | 31.54 | 1133.86 | | 1143.00 | | | Namurian | ? |
| Egmanton | No.6 | I,P | SK 70670.69000 | 24.76 | 1164.03 | | 1173.78 | | Bitumen in limestone | Namurian | ? |
| Egmanton | No.11 | I,P | SK 75120.67700 | 44.89 | 1143.91 | | 1156.72 | | | Namurian | ? |
| Egmanton | No.13 | I,P | SK 73410.69600 | 30.05 | 1216.76 | | 1225.30 | | | Namurian | ? |
| Egmanton | No.19 | I,P | SK 75590.67610 | 23.32 | 1115.57 | | 1122.88 | | | Namurian | ? |
| Ellistown | | D,B | SK 43900.10560 | 170.69 | 467.87 | | 494.08 | | Dolomitic, 'quartz dust', dolomite vein, iron pyrite and chert | Namurian | ? |
| Eyam | | K | SK 20960.76030 | 230.12 | 000.00 | 1803.25 | 1851.05 | $C_1$,$C_2$-$S_1$,$S_2$,$D_1$,$D_2$ | Dolomitic,anhydrite,tuff,lava + bitumen | N/A | Llanvirn |
| Farndon | No.1 | F | SK 76613.54453 | 12.80 | 777.85 | | 804.06 | | | Namurian | ? |
| Farndon | No.2 | F | SK 76914.53117 | 13.41 | 771.75 | | 775.72 | | | Namurian | ? |
| Foston | No.1 | C | SK 84894.41470 | 28.35 | 466.34 | 614.17 | 782.28 | $S_2$,$D_2$ | | Permian | Charnian ? |
| Granby | No.1 | F | *SK 75316.36836 | 38.10 | 904.65 | | 939.09 | | | Namurian | ? |
| Granby | No.2 | F | *SK 76890.36533 | 31.39 | 905.86 | | 909.22 | | | Namurian | ? |
| Grove | No.1 | J | SK 75230.80700 | 68.27 | 1551.43 | | 1573.07 | $P_2$? | | Namurian ($E_1$) | ? |
| Hardstoft | No.1 | H | SK 44340.62380 | 192.02 | 937.87 | | 997.31 | | | | |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | Namurian | | ? |
| Hathern | No.1 | F | *SK 51594.24149 | 49.07 | 387.71 | | 634.59 | $C_1$-$C_2$? | Anhydrite beds, veins | Namurian | | ? |
| Heath | | H | SK 44520.66740 | 157.28 | 1194.82 | | 1221.94 | | Pyrite | Namurian | | ? |
| High Marnham | | I,P | SK 80930.70285 | 10.36 | 1143.00 | | 1158.24 | | | Namurian | | ? |
| Highoredish | | H | SK 35410.60320 | 184.40 | 85.65 | | 157.89 | $D_2$,P | Chert, olivine-basalts,$CaF_2$+ ZnS vein at 116.4m. | Namurian ($E_1$) | | ? |
| Hockerton | No.2 | F,I | *SK 69583.58081 | 75.59 | ∿852.83 | | 899.16 | | | Namurian | | ? |
| Ironville | No.1 | M | SK 43070.51300 | 102.11 | 620.27 | | 1114.04 | $D_1$,$D_2$,$P_2$ | Chert, dolomite, pyrite quartz + dolerites/tuffs | Namurian | | ? |
| Ironville | No.2 | A,H,M | SK 43620.55620 | 150.57 | 923.24 | | 1221.03 | $D_1$,$D_2$,$P_2$ | Chert, tuffs, agglomerates, toadstone | Namurian | | ? |
| Ironville | No.3 | F,H,M | SK 43250.52320 | 124.05 | ∿680.62 | | 835.76 | $D_1$?,$P_2$ | $CaF_2$ veins | Namurian | | ? |
| Johannesburg | No.9 | H | SK 30370.59010 | 205.74 | 115.21 | | 165.51 | $D_2$,$P_2$ | Chert, pseudobreccias, lava | Namurian | | ? |
| Kelham Hills | No.1 | I,P | SK 75940.57620 | 52.45 | ∿735.18 | | 767.94 | | | Namurian | | ? |
| Kelham Hills | No.15 | I,P | SK 76480.57800 | 41.45 | 692.81 | | 699.21 | | | Namurian | | ? |
| Kelham Hills | No.39 | I,P | SK 76290.57230 | 42.67 | 690.68 | | 704.09 | | | Namurian | | ? |
| Kelham Hills | No.52 | I,P | SK 76500.57580 | 56.39 | 732.43 | | 736.09 | | | Namurian | | ? |
| Kirklington | No.1 | I,F | *SK 69290.56300 | 29.87 | ∿840.64 | | 852.22 | | | Namurian | | ? |
| Kiveton | No.1 | E | SK 48940.84120 | 100.89 | 1386.84 | | 1415.49 | | Fractures, FeS,$CaCO_3$, silicified | Namurian | | ? |
| Langar | No.1 | F | *SK 71988.35577 | 31.70 | 946.10 | | 986.33 | | | Namurian | | ? |
| Long Clawson | | O | SK 73500.28410 | 54.25 | 1331.98 | | 1434.08 | | Igneous horizons | Namurian | | ? |
| Mansfield (BP) | No.1 | F,I | *SK 55500.59055 | 134.11 | ∿1325.88 | | 1368.55 | | Spicular chert, bituminous | Namurian | | ? |
| Mansfield (AA) | | I,P | SK 55500.59100 | 132.45 | ∿1330.45 | | 1374.34 | | Cherty Limestone | Namurian | | ? |
| Maplebeck | No.1 | I,P | *SK 70529.60101 | 83.21 | ∿916.53 | | 928.73 | | | Namurian | | ? |
| Melbourne(High Wood) | B | P | SK 38200.23740 | 89.30 | 163.22 | | 168.95 | | | Namurian | | ? |
| Nocton | No.1 | C | *TF 05106.64661 | 28.04 | 914.40 | 1173.79 | 1181.71 | $C_1$,$S_2$? | | Namurian | Cambrian | ? |
| Nocton | No.2 | C,P | TF 02079.65257 | 54.86 | 954.63 | | 957.38 | $D_1$? | Dinantian oil producer | Namurian | | ? |
| Nocton | No.3A | C | TF 01956.65517 | 56.08 | 957.68 | | 972.31 | | | Namurian | | ? |
| Nocton | No.4 | C | TF 01867.65349 | 57.61 | 964.08 | | 967.43 | | | Namurian | | ? |
| Nocton | No.5 | C | TF 02233.65264 | 54.56 | 957.07 | | 967.74 | | | Namurian | | ? |
| Nocton | No.6 | F | *TF 01913.64864 | 57.61 | 960.12 | | 990.60 | $S_2$? | | Westphalian | Lower Visean | |
| Nocton South | No.1 | C | *TF 02956.63956 | 50.29 | 935.43 | | 940.92 | | | Namurian | | ? |
| Normanton | No.1 | C | *SK 71942.54384 | 30.78 | 847.34 | | 850.09 | | | Namurian | | ? |
| Normanton | No.3 | I,P | SK 71610.54850 | 49.68 | ∿882.40 | | 903.73 | | | Namurian | | ? |
| Normanton | No.4 | F | *SK 72189.54431 | 23 47 | 793.39 | | 871.42 | | | Namurian | | ? |
| Pickworth Plot | | R | SK 89597.68678 | 31.80 | 1018.50 | | 1077.66 | | Stylolitic | Westphalian | | ? |
| Plungar | No.1 | F | *SK 77206.33479 | 64.92 | 935.13 | | 944.27 | $D_1$? | | Namurian | | ? |
| Plungar | No.13 | O,P | SK 77260.31940 | 65.23 | 929.03 | | 935.74 | | | Namurian | | ʻ |
| Renishaw | | A,E | SK 42650.77830 | 90.53 | 1249.68 | | 1290.83 | | Silicified sandstone,limestone + chert | Namurian | | ? |
| Ridgeway | | A,E | SK 40060.81520 | 155.14 | 877.82 | | 913.18 | | | Namurian | | ? |
| Rolleston | No.1 | C | *SK 76122.51905 | 15.24 | 685.19 | | 725.42 | | | Namurian | | ? |
| Rolleston | No.2 | C | *SK 74912.51132 | 16.76 | 717.80 | | 722.07 | | | Namurian | | ? |
| Rolleston | G2 | C | *SK 75300.51348 | 14.33 | 655.93 | | 666.90 | | | Namurian | | ? |
| Rotherwood | | L | SK 34580.15587 | 109.50 | 61.49 | 173.90 | 199.00 | $D_2$ | Dolomitic, pseudobreccias | Namurian | Post Middle Cambrian | |
| Ruskington | No.1 | F | *TF 09207.49746 | 10.97 | 1000.49 | | 1002.49 | $D_1$ | | Namurian | | ? |
| Screveton | No.1 | F | *SK 73075.43483 | 25.91 | 1053.69 | | 1103.68 | | | Namurian | | ? |
| Somerton | No.1 | N | *TG 46164.19349 | 00.00 | 1040.28 | 1365.81 | 1396.56 | S,D and Thick P | Veins and geodes. PbS,FeS,$CaCO_3$ | Namurian | Silurian | ? |
| South Leverton | No.1 | J | SK 79330.80400 | 11.28 | ∿1514.86 | | 1562.10 | D?,P? | Dolomitisation | Namurian ($E_1$) | | ? |
| Spital | No.1 | C | *SK 96531.91143 | 44.81 | 1698.65 | | 1705.05 | $D_2$? | | Namurian | | ? |
| Stixwould | No.1 | C,G | *TF 18846.65308 | 8.23 | 1386.84 | 1441.70 | 1454.20 | C (part of) | Signs of hydrothermal alteration in basement | Namurian | Pre-Cambrian/Cambrian | |
| Stockshouse Farm | | D,O,P | SK 46800.02120 | 121.92 | 143.86 | 152.09 | 152.09 | P | | Namurian | | ? |
| Sutton-on-Trent | No.1 | C | SK 79490.62490 | 11.28 | 999.44 | | 1004.32 | | | Namurian | | ? |
| Sutton-on-Trent | No.2 | C | SK 79950.64950 | 10.67 | 1025.65 | | 1028.70 | | | Namurian | | ? |
| Sutton-on-Trent | No.3 | F | *SK 79130.63775 | 12.19 | 1008.28 | | 1026.26 | | | Namurian | | ? |
| Tansley | | H | SK 33130.59600 | 201.78 | 307.24 | | 348.08 | | Base metals concentrated in black shales | Namurian ($E_1$) | | ? |
| Thorpe | No.1 | F | *SK 76922.50530 | 14.63 | 683.67 | | 691.90 | | | Namurian | | ? |
| Trumfleet | No.1 | F | *SE 60510.12588 | 8.23 | 1524.30 | | 1580.08 | | | Namurian | | ? |
| Trusley | | M | SK 25480.35880 | 79.25 | 101.50 | | 154.53 | $D_1$(at base) | Gypsum, veinlets and faults | Triassic | | ? |
| Tuxford | No.1 | F | *SK 72180.70500 | 78.18 | 1281.38 | | 1294.18 | | | Namurian | | ? |
| Uppertown | | H | SK 32370.64250 | 211.83 | 160.63 | | 176.78 | | | Namurian ($E_1$) | | ? |
| Westfield Lane | | R | SK 91990.41721 | 44.87 | 643.00 | | 679.60 | Brigantian -late Asbian. | Dolomite, some galena and pyrite | Namurian | | ? |
| Whittington | No.1 | E,F | SK 38430.75790 | 141.43 | 1003.10 | | 1026.87 | | Silicification | Namurian | | ? |
| Widmerpool | No.1 | F | *SK 63657.29583 | 81.08 | 1325.88 | | 1890.98 | L.Carb. Shales | | Namurian | Lower Carboniferous Shale | |

A - Giffard (1923); B - Boulton (1934); C - Lees and Tait (1946); D - Mitchell and Stubblefield (1948);
E - Eden et al. (1957); F - Falcon and Kent (1960); G - Kent (1967); H - Smith et al. (1967);
I - Edwards (1967); J - Smith et al. (1973); K - Dunham (1973); L - Institute of Geological Sciences (1978);
M - Frost and Smart (1979); N - Conoco (pers.comm.); O - Institute of Geological Sciences (pers. comm.),
P - British Petroleum (pers.comm.); R - National Coal Board (pers.comm.).

Although the deposition of the bulk of the base metals and gangue minerals has been confined to calcareous environments, in which local aquicludes may have acted as temporary cap-rocks (Firman & Bagshaw, 1974; Walters & Ineson, 1981) the more mobile phases appear to have 'leaked' or migrated into the overlying Upper Carboniferous, Permian and Triassic sediments. In these horizons, their passage has been facilitated by major faults, often reactivated, as at Whitwell. Deposition, principally confined to barite-calcite + galena, is vein-like with subordinate replacement flats or wholesale metasomatic alteration of suitably porous units, e.g. oolitic Magnesian Limestone. In such circumstances, leakage deposition is proposed. Considering the palaeogeographical conditions of this epoch, it may well be that episyngenetic or syngenetic (stratabound-stratified) deposits have also resulted on a local scale. Isotopic evidence supports a multi-component model with intermixing at high structural and stratigraphical levels. The scattered occurrences in the Upper Carboniferous and Permo-Trias may well indicate a transitional environment between the thermal zoning at depth and escape at the surface into the Triassic groundwaters.

A contour plot of data from boreholes in the East Midlands supports the hypothesis of the mineral field extending in depth beneath the younger strata of the East Midlands, probably as far as the coast.

## Acknowledgements

The authors appreciate the information provided by East Midlands and Northern England Units of the Institute of Geological Sciences, whilst Conoco (U.K.) Ltd. are thanked for details of the Somerton Borehole, and BP for additional data not previously published.

H.M. Nautical Almanac Office, Royal Greenwich Observatory kindly converted borehole localities (latitude-longitude) to National Grid reference figures.

R.W. Vernon and D.E. Raisbeck of the National Coal Board's geological staff are thanked for providing information on mineral localities noted during mining or exploration for coal.

Mr. P. Leman and the staff of the University of Sheffield's Computer Department are thanked for assistance in the execution of the GHOST (GrapHical Output SysTem) and GINO-SURF (Graphical INput/Output - SURFace) packages of the Culham Laboratories of the U.K.A.E.A. and the University of Salford respectively.

Professor C. Downie kindly provided detailed information on the stratigraphical horizon of certain basement horizons.

Sir Peter Kent, Sir Kingsley Dunham and Dr. C.I. Fletcher critically reviewed the manuscript and provided additional information for which they are thanked.

P.R. Ineson, B.Sc., Ph.D.,
C.Eng., M.I.M.M., F.G.S.
Department of Geology,
University of Shefield

T.D. Ford, B.Sc., Ph.D., F.G.S.
Department of Geology,
University of Leicester

## References


BEALES, F.W. & JACKSON, S.A. 1966. Precipitation of lead-zinc ores in carbonate reservoirs as illustrated by Pine Point Orefield, Canada. *Trans. Instn. Min. Metall. (Sect. B: Appl. Earth Sci.)*, vol.75, pp.278-285.

BEALES, F.W. & ONASICK, E.P. 1970. Stratigraphic habitat of Mississippi Valley type ore bodies. *Trans. Instn. Min. Metall. (Sect. B: Appl. Earth Sci.)*, vol.79, pp.145-154.

BOTT, M.H.P. 1967. Geophysical investigations of the northern Pennine basement rocks. *Proc. Yorks. Geol. Soc.*, vol.36, pp.139-168.

BOULTON, W.S. 1934. The Sequence and Structure of the South-east portion of the Leicestershire Coalfield. *Geol. Mag.*, vol.71, pp.323-329.

BROWN, G.C., CASSIDY, J., OXBURGH, E.R., PLANT, J., SABINE, P.A. & WATSON, J.V. 1980. Basement heat flow and metalliferous mineralization in England and Wales. *Nature*, vol.288, pp.657-659.

BULLARD, E.C. & NIBLETT, E.R. 1951. Terrestrial Heat Flow in England. *Roy. Astron. Soc. Monthly Notes, Geophys. suppl.*, vol.6, pp.222-238.

BUSH, P.R. 1970. Chloride-rich brines from sabka sediments and their possible role in ore formation. *Trans. Instn. Min. Metall. (Sect. B: Appl. Earth Sci.)*, vol.79, pp.137-144.

CARLON, C.J. 1979. *The Alderley Edge Mines.* pub. John Sherratt, Altrincham, 144pp.

COOMER, P.G. & FORD, T.D. 1975. Lead and sulphur isotope ratios of some galena specimens from the South Pennine and north Midlands. *Mercian Geol.*, vol.5, pp.291-304.

DAVIDSON, C.F. 1966. Some genetic relationships between ore deposits and evaporites. *Trans. Instn. Min. Metall. (Sect. B: Appl. Earth Sci.)*, vol.75, pp.216-225.

DEANS, T. 1961. A galena-wulfenite-uraniferous asphaltic horizon in the Magnesian Limestone of Nottinghamshire. *Miner. Mag.*, vol.252, pp.705-715.

DOWNING, R.A. 1967. The geochemistry of groundwaters in the Carboniferous Limestone in Derbyshire & the East Midlands. *Bull. Geol. Surv. GB*, no.27, pp.289-307.

DOWNING, R.A. & HOWITT, F. 1969, Saline ground-waters in the Carboniferous Rocks of the English East Midlands in relation to the geology. *Q. Jl. Eng. Geol. London*, vol.1, pp.241-269.

DOZY, J.J. 1970. A geological model for the genesis of the lead zinc ores of the Mississippi Valley. *Trans. Instn. Min. Metall. (Sect. B: Appl. Earth Sci.)*, vol.79, pp.163-170.

DUNHAM, K.C. 1948. Geology of the Northern Pennine Orefield. *Mem. Geol. Surv. GB*, vol.1. Tyne to Stainmore, HMSO, London, 357pp.

DUNHAM, K.C. 1952. Fluorspar. *Spec. Rep. Mineral. Resour. GB*, vol iv (4th Ed.) - *Mem. Geol. Surv. GB*, HMSO, London, 143pp.

DUNHAM, K.C. 1961. Black Shale, Oil and Sulphide Ore. *Adv. Sci.*, vol.18, no.73, pp.1-16.

DUNHAM, K.C. 1966. The role of juvenile solutions, connate waters and evaporite brines in the genesis of lead, zinc, fluorite, barite deposits. *Trans. Instn. Min. Metall. (Sect. B: Appl. Earth Sci.)*, vol.75, pp.226-229.

DUNHAM, K.C. 1967. Mineralization in relation to the Pre-Carboniferous basement rocks, Northern England. *Proc. Yorks. Geol. Soc.*, vol.36, pp.195-201.

DUNHAM, K.C. 1970. Mineralisation by deep formation waters: a review. *Trans. Instn. Min. Metall. (Sect. B: Appl. Earth Sci.)*, vol.79, pp.127-136.

DUNHAM, K.C. 1973. A recent deep borehole near Eyam, Derbyshire, *Nature, Phys. Sci.*, vol.241, pp.84-85.

EDEN, R.A., STEVENSON, I.P. & EDWARDS, W. 1957. Geology of the Country around Sheffield. *Mem. Geol. Surv. GB*, 238pp.

EDMUNDS, W.M. 1971. Hydrogeochemistry of groundwaters in the Derbyshire Dome with special reference to trace constituents. *Rept. Inst. Geol. Sci.*, HMSO, Lond., vol.71/7, 52pp.

EDWARDS, W.N. 1967. Geology of the Country around Ollerton. *Mem. Geol. Surv. GB*, 297pp.

EVANS, A.M. & MAROOF, S.I. 1976. Basement controls of mineralisation in the British Isles. *Mining Mag.*, vol.134, pp.401-411.

EMBLIN, R. 1978. A Pennine Model for the Diagenetic Origin of Base-metal Ore Deposits in Britain. *Bull. Peak Dist. Mines Hist. Soc.*, vol.7 (1), pp.5-20.

FALCON, N.L. & KENT, P.E. 1960. Geological results of petroleum exploration in Britain, 1945-1957, *Mem. Geol. Soc. Lond.*, no.2, 56pp.

FIRMAN, R.J. & BAGSHAW, C. 1974. A re-appraisal of the controls of non-metallic gangue mineral distribution in Derbyshire. *Mercian Geol.*, vol.5, pp.145-161.

FORD, T.D. 1961. Recent studies of mineral distribution in Derbyshire and their significance. *Bull. Peak Dist. Mines Hist. Soc.*, vol.2, no.1, pp.3-9.

FORD, T.D. 1976. *The ores of the south Pennines and Mendip Hills, England - a comparative study.* In - *Handbook of stratabound and stratiform ore deposits*, vol.5, *regional studies*, Wolf, K.M., ed. (Amsterdam: Elsevier, 1976), pp.161-195.

FORD, T.D. & INESON, P.R. 1971. The fluorspar mining potential of the Derbyshire ore field. *Trans. Instn. Min. Metall. (Sect. B: Appl. Earth Sci.)*, vol.80, pp.216-210.

FORD, T.D. & KING, R.J. 1968. Mineralisation of the Triassic rocks of South Derbyshire. *Trans. Instn. Min. Metall. (Sect. B: Appl. Earth Sci.)*, vol.77, pp.42-43.

FROST, D.V. & SMART, J.G.O. 1979. Geology of the County north of Derby. *Mem. Geol. Surv. GB*, 199pp.

GIFFARD, H.P.W. 1923. The Recent Search for Oil in Great Britain. *Trans. Instn. Min. Eng.*, vol.65, pp.221-250.

HEYL, A.V. 1967. Some aspects of genesis of stratiform zinc-lead-Barite-Fluorite deposits in the United States in Genesis of Stratiform Lead-Zinc-Barite-Fluorite Deposits, ed. by J.S. Brown, *Econ. Geol. Monogr.*, no.3, pp.20-32.

HIRST, D.M. & DUNHAM, K.C. 1963. Chemistry and Petrography of the Marl Slate of SE Durham, England. *Econ. Geol.*, vol.58, pp.912-940.

HIRST, D.M. & SMITH, F.W. 1974. Controls of barite mineralisation in the Lower Magnesium Limestone of the Ferryhill area County Durham. *Trans. Instn. Min. Metall. (Sect. B: Appl. Earth Sci.)*, vol.83, pp.B49-55.

HOLLAND, H.D. 1979. Metals in black shales - A reassessment. *Econ. Geol.* vol.74, pp.1676-80.

HOWITT, F. & BRUNSTROM, R.G.W. 1966. The continuation of the East Midlands Coal Measures into Lincolnshire. *Proc. Yorks. Geol. Soc.*, vol.35, pp.549-564.

INESON, P.R. & AL-KUFAISHI, F.A.M. 1970. The Mineralogy and paragenetic sequence of Long Rake vein at Raper Mine, Derbyshire. *Mercian Geol.*, vol.3, pp.337-351.

INESON, P.R. & MITCHELL, J.G. 1972. Isotopic age determinations on clay minerals from lavas and tuffs of the Derbyshire orefield. *Geol. Mag.*, vol.109, pp.501-512.

INESON, P.R., RICHARDSON, R.T. & WOOD, G.H. 1972. A baryte-galena veins in the Magnesian Limestone at Whitwell, Derbyshire. *Proc. Yorks. Geol. Soc.*, vol.39, pp.139-149.

INST. GEOL. SCI. 1965. *Aeromagnetic map of Great Britain.* Sheet 2.

INST. GEOL. SCI. *Annual Report* for 1966, HMSO, London, 1967. 197p. (pp.64 & 67).

INST. GEOL. SCI. 1978. I.G.S. Boreholes 1977. *Inst. Geol. Sci. Report*, HMSO, London, 78/21.

KENT, P.E. 1966. The structure of the concealed Carboniferous rocks of north-eastern England. *Proc. Yorks. Geol. Soc.*, vol.35, pp.323-352.

KENT, P.E. 1967. A contour map of the sub-Carboniferous surface in the north-east Midlands. *Proc. Yorks. Geol. Soc.*, vol.36, pp.127-133.

KENT, P.E. — 1968. *The buried floor of eastern England,* in *The Geology of the East Midlands*, ed. by P.C. Sylvester-Bradley & T.D. Ford (Leicester: Leic. Univ. Press), pp.138-148.

KING, R.J. — 1966. Epi-syngenetic mineralisation in the English Midlands. *Mercian Geol.*, vol.1, pp.291-301.

LE BAS, M.J. — 1972. Caledonian igneous rocks beneath central and eastern England. *Proc. Yorks. Geol. Soc.*, vol.39, pp.71-86.

LEES, G.M. & TAITT, A.H. — 1946. The geological results of the search for oilfields in Great Britain. *Q. Jl. Geol. Soc., Lond.*, vol.101, pp.255-317.

LLEWELLYN, P.G. & STABBINS, R. — 1968. Lower Carboniferous evaporites and mineralisation in the eastern and central Midlands of Britain. *Trans. Instn. Min. Metall. (Sect. B: Appl. Earth Sci.)*, vol.77, pp.B170-173.

LLEWELLYN, P.G. & STABBINS, R. — 1970. The Hathern Anhydrite Series, Lower Carboniferous, Leicestershire, England. *Trans. Instn. Min. Metall. (Sect. B: Appl. Earth Sci.)*, vol.79, pp.B1-15.

MITCHELL, R.H. & KROUSE, H.R. — 1971. Isotopic composition of sulphur and lead in galena from the Greenhow-Skyreholme area, Yorkshire, England. *Econ. Geol.*, vol.66, pp.243-251.

MITCHELL, G.H. & STUBBLEFIELD, C.J. — 1948. The Geology of the Leicestershire and South Derbyshire Coalfield. *Mem. Geol. Surv. GB, Wartime Pamph.*, no.22, 2nd ed., 48p.

MONTELEONE, P.H. — *The Geology of the Carboniferous Limestone of Leicestershire and south Derbyshire.* Ph.D. Thesis Univ. of Leicester.

MOORBATH, S. — 1962. Lead isotope abundance studies on minerals in the British Isles and their geological significance. *Phil. Trans. R. Soc.*, A254, pp.295-360.

MUELLER, G. — 1951. *A genetical and geochemical survey of the Derbyshire mineral deposits.* Ph.D. thesis, University of London, 310pp.

MUELLER, G. — 1954a. The distribution of coloured varieties of fluorites within the thermal zones of Derbyshire mineral deposits. *19th Int. geol. Congr.*, Algiers, 1952 (Algiers: The Congress, 1954), vol.15, pp.523-539.

MUELLER, G. — 1954b. The theory of the genesis of oil through hydrothermal alteration of coal-type substances within the Lower Carboniferous strata of the British Isles. *19th Int. geol. Congr.* Algiers 1952 (Algiers: The Congress, 1954) no.12, pp.279-328.

OHLE, E.L. — 1967. The Origin of Ore Deposits of the Mississippi Valley Type in Genesis of Stratiform Lead-Zinc-Barite-Fluorite Deposits, ed. by J.S. Brown. *Econ. Geol. Monogr.*, no.3, pp.33-39.

PERING, K.L. — 1973. Bitumens associated with lead, zinc and fluorite ore minerals in North Derbyshire, England. *Geochim. Cosmochim. Acta*, vol.37, (3), pp.401-417.

RAMSBOTTOM, W.H.C. RHYS, G.H. & SMITH, E.G. 1962. Boreholes in the Carboniferous rocks of the Ashover district, Derbyshire. *Bull. geol. Surv. GB*, no.19, pp.75-168.

ROBINSON, B.W. & INESON, P.R. 1979. Sulphur, oxygen and carbon isotope investigations of lead-zinc-barite-fluorite-calcite mineralisation, Derbyshire, England. *Trans. Instn. Min. Metall. (Sect. B: Appl. Earth Sci.)*, vol.88, pp.B107-117.

ROGERS, P.J. 1977. Fluid inclusion studies in fluorite from the Derbyshire orefield. *Trans. Instn. Min. Metall. (Sect. B: Appl. Earth Sci.)*, vol.86, pp.B128-132.

RUSSELL, M.J. 1976. Incipient plate separation and possible related mineralisation in lands bordering the North Atlantic. In Metallogeny and Plate Tectonics, ed. by Strong, D.F. *Geol. Assoc. Can. Spec. Pap.*, no.14, pp.339-349.

RUSSELL, M.J. 1978. Mineralisation in a fractured craton, in Crustal evolution in northwestern Britain and adjacent regions, ed. by Bowes, D.R. & Leake, B.E., *Geol. Jl. Spec. Issue*, no. 10, pp.297-308.

SCHNELLMANN, G.A. 1955. Concealed lead-zinc fields in England. *Trans. Instn. Min. Metall.*, vol.64, pp.477-485; discussion pp.617-636.

SCHNELLMANN, G.A. & WILLSON, J.D. 1947. Lead-zinc mineralisation in North Derbyshire. *Bull. Inst. Min. Metall.*, no.485, Apr., pp.1-14 and Aug. pp.19-34, Oct. pp.17-18. *Trans. Instn. Min. Metall.* vol.56, pp.549-585.

SHIRLEY, J. 1959. The Carboniferous Limestone of the Monyash-Wirksworth area, Derbyshire, *Q. Jl. Geol. Soc. Lond.*, vol.114, pp.411-429.

SHIRLEY, J. & HORSFIELD, E.L. 1945. The structure and ore deposits of the Carboniferous Limestone of the Eyam district of Derbyshire. *Q. Jl. Geol. Soc. Lond.*, vol.96, pp.271-299.

STEVENSON, I.P. & GAUNT, G.D. 1971. Geology of the Country around Chapel-en-le-Frith. *Mem. Geol. Surv. GB*, 443pp.

SMITH, E.G., RHYS, G.H. & EDEN, R.A. 1967. Geology of the Country around Chesterfield, Matlock and Mansfield. *Mem. Geol. Surv. GB*, 430pp.

SMITH, E.G., RHYS, G.H. & GOOSSENS, R.F. 1973. Geology of the Country around East Retford, Worksop and Gainsborough. *Mem. Geol. Surv. GB*, 348pp.

SMITH, F.W. 1973. Fluid inclusion studies on fluorite from the North Wales ore field. *Trans. Instn. Min. Metall. (Sect. B: Appl. Earth Sci.)*, vol.82, pp.B174-176.

SMITH, F.W. 1974. Factors governing the development of fluorspar orebodies in the Northern Pennine Orefield. Ph.D. Thesis, University of Durham.

SPEARS, D.A. & AMIN, M.A. 1981. Geochemistry and Mineralogy of Marine and Non-Marine Namurian Black Shales from the Tansley Borehole, Derbyshire. *Sedimentology*, vol.28, pp.407-418.

TAYLOR, F.W. & HOLDSWORTH, A.R.E. 1973. The distribution of barite in Permo-Triassic Sandstones at Bramcote, Stapleford, Trowell and Sandiacre, Nottinghamshire. *Mercian Geol.*, vol.4, pp.171-177.

VINE, J.D. & TOURTELOT, E.B. 1970. Geochemistry of black shale deposits - A summary report. *Econ. Geol.*, vol.65, pp.253-272.

WALTERS, S.G. & INESON, R.R. 1981. A review of the distribution and correlation of igneous rocks in Derbyshire, England. *Mercian Geol.*, vol.8, pp.81-132.

WEDD, C.B. & DRABBLE, G.C. 1908. The fluorspar deposits of Derbyshire. *Trans. Instn. Min. Eng.*, vol.35, pp.501-535.

WHITE, D.E. 1968. Environment of generation of some base metal deposits. *Econ. Geol.*, vol.63, pp.301-335.

WHITE, P.H.N. 1948. Gravity data obtained in Great Britain by the Anglo-American Oil Company Limited. *Q. Jl. geol. Soc. Lond.*, vol.104, pp.339-364.

WORLEY, N.E. & FORD, T.D. 1977. Mississippi Valley type orefields in Britain. *Bull. Peak Dist. Mines Hist. Soc.*, vol.6, pp.201-208.

EXCURSION TO ANGLESEY

Leader: A.M. Evans — Saturday and Sunday, 16 & 17 May, 1981

The object of the excursion was to examine some of the interesting and very varied geology that can be seen on the island. With only two days available the choice of exposures to be visited had to be very selective and only a few aspects of Anglesey could be inspected.

Most of the party assembled at the Holborn Hotel in Holyhead on the Friday evening when the leader gave a brief résumé of the geology of Anglesey and some details of the localities that would be visited.

SATURDAY, 16 MAY

Rhoscolyn and South Stack

The party proceeded to Rhoscolyn Church, on Holy Island, (SH 268.757) where other members of the Society were waiting. A short walk took us to the coast at 268.747 where some of the lowest exposed beds in the Monian Supergroup were examined. These are exposed in the large Rhoscolyn Anticline, an asymmetric fold having a south-easterly vergence and a north-easterly plunge. It is now believed to be an $F_2$ structure which appears to be complex owing to the presence of locally intense mesoscopic parasitic folding and later superposed deformations. The cleavage, which grades in places into a schistosity, is axial planar and fans across the fold with an average north-westerly dip of about 60°.

The first outcrops examined belong to the Rhoscolyn Formation. They are schistose quartzo-feldspathic turbidites with some intercalated quartzites. Graded-bedding shows that the majority of the minor folds face upwards and that the beds as a whole, which are steeply dipping to over-turned, young south-eastwards. This evidence supports the above structural interpretation due to Shackleton (1969) and disproves Greenly's (1919) hypothesis of major recumbent folding. Quartz veins are developed parallel to the cleavage and these and the cleavage are deformed by a later phase of folding.

Proceeding north-westwards the party came to a low rock face, the top of the Holyhead Quartzite. This is a very pure rock in which bedding cannot usually be discerned. Shackleton has suggested that it might be a submarine sand flow deposit. A well developed pressure solution cleavage pervades the rock. After rounding two deep fault-located inlets the party walked on to the South Stack Formation in the core of the major anticline. Here the strata are shallow dipping to horizontal and the small scale fold symmetry could be seen to change its attitude across the hinge zone of the anticline.

The party returned to the coastal path near St. Gwenfaen's Well where the Holyhead Quartzite in the north-western limb of the fold could be seen resting conformably on the South Stack Formation. Continuing along the coastal path the party crossed the Quartzite and were once more on the Rhoscolyn Formation. Fine erosional features were seen along this part of the traverse including a blowhole and sea arches. In a cave in Bwa Gwyn Cove possible giant flute casts in a quartzite band were inspected. Above the quartzite more outcrops of schistose greywackes of the Rhoscolyn Formation were crossed until Bwa Du (260.763) was reached. Here schists of the overlying New Harbour Group are faulted against the Rhoscolyn Formation. After examining structural features in schists the party returned to the vehicles and drove to 268.772.

At this inland locality serpentinites can be seen emplaced in the New Harbour Group. These have been suggested by some workers to be slices of ocean floor tectonically emplaced in their present position. Recently Maltman (1975) has argued that they were magmatically emplaced, his principal evidence being the partial existence of a thermal aureole. A small quarry in highly sheared dark green serpentinite was first examined and than a prominent mound of altered gabbro.

Mercian Geologist, vol. 8, no. 4,
1982, pp. 305-307.

A drive via Trearddur brought the party to the South Stack where members descended the many steps to the bridge across to the lighthouse. From just across the bridge a fine view of the folded greywackes of the South Stack Formation was much appreciated by the party who also took time off on the ascent to view the spectacular large scale folds in vertical cliff faces to the right of the path. The party then proceeded via Holyhead and the Embankment to Valley cross-roads turning on to the Amlwch road. A short stop was made here to view the drumlins before proceeding to Tre-Fadog.

Tre-Fadog (292.862)

The cars were parked by the foreshore and the party walked across to reefs at the northern end of the bay. Here rocks of the Church Bay Tuffs (the upper formation of the Skerries Group) were examined. These fine-grained acidic volcanics appear to be tuffs; as they lack stratification they may be ignimbrites. From this point there was a fine view of Holy Island including New Harbour and the aluminium smelter. The party then returned by car to the A5 and followed it south-eastwards to the turning for Rhosneigr.

Rhosneigr (319.732)

After parking in the main town car park the party walked to the foreshore where Ordovician rocks are exposed. They consist mainly of black slates with thin beds of sandstones. The sandstone layers reveal that the rocks are folded about north-easterly plunging axes. The folds are asymmetrical with a south-easterly vergence. Cleavage in the slates is axial planar to these folds. Crossing the sand to the nearby reefs enabled the party to examine the coarse basal conglomerates of Arenig age. A variety of clasts were identified all of which could be correlated with rock types in The Monian Supergroup. The party then returned to Holyhead.

SUNDAY, 17 MAY

Cemaes Bay area (SH 374.937)

The party drove to the car park at the eastern side of the bay and walked on to the foreshore to examine the rock exposures in the low cliffs. These outcrops are in the Gwna Mélange Formation of the Gwna Group and consist of large blocks of limestone and other rock types in a fine-grained matrix. Greenly (1919) interpreted these deposits as an autoclastic mélange formed by tectonic deformation of a normal sedimentary sequence to form large scale boudinage structures. Shackleton in 1969 suggested that the mélange represents an olistostrome, a sedimentary deposit formed by large scale submarine mass sliding of part of the Gwna Group succession.

The excursion then followed the cliff top path to the limestone quarry at 372.942 to examine the exposures where the stromatolites described by Wood & Nicholls (1973) were collected. After a vain search for oncolites in the quarry the party moved to the coastal exposures where banded and mound-shaped stromatolites were examined. Moving down dip the party inspected the contact between the limestone and the Gwna Mélange. The party then proceeded to Parys Mountain.

Parys Mountain (442.903)

In the early nineteenth century Parys Mountain was Europe's principal copper producer. During that century its importance slowly declined and mining ceased before the First World War. The vehicles were parked at 438.907 and the party walked in to the edge of the Great or Western Opencast. From this vantage point the director pointed out the main items of geological interest and explained the general synclinal structure of the locality. The party then walked round to the south side of the pit to examine the rhyolitic volcanics before descending into the opencast. Here a quartz-pyrite stockwork in silicified slates was examined and specimens of galena, sphalerite and chalcopyrite were collected from nearby exposures. Some of the party made a quick but unsuccessful search for monograptids in the Silurian slates. The party then moved on to examine the Devonian.

The Old Red Sandstone

A stop was made to examine the basal Old Red Sandstone conglomerates (Bodafon Formation) at Mynydd Bodafon (476.855). These deposits occur in roadside outcrops apparently stacked against a fossil hill of Precambrian quartzite. The party then moved on to Lligwy Bay and traversed northwards down the Old Red Sandstone succession noting the facies, cleavage and slight folding. First to be encountered were the probable lacustrine rocks of the Traeth Lligwy Formation. These consist of alternations of fine-grained red sandstones and sandy siltstones but without carbonates. Trace fossils occur in places and occasional mud cracks are present.

Beneath this formation the more varied rocks of the Porth y Mor Formation occur. Allen (1965) considered these rocks to have been laid down in a complex braided river system. They consist of a cyclical succession of purple cross-bedded sandstones, red concretionary siltstones and concretionary limestones and dolomites (calcretes). A typical cycle commences with an intraformational conglomerate which is followed by cross-bedded sandstone deposited in a stream course. In places the sandstones grade upwards into siltstones with calcrete limestone and dolomite. These have been interpreted as overbank deposits with the carbonates forming during periods of prolonged exposure. After a quick inspection of these beds the party returned to the vehicles.

Llandysilio (539.736)

At the request of the President a special stop was made here to visit outcrops of glaucophane-schists. These blue schists have been shown by Thorpe (1972) to be metamorphosed ocean floor basalts. They were the most highly metamorphosed rocks to be examined during the weekend and members of the party were interested in the various schistosities and lineations which could be identified in the exposures.

A.M. Evans,
Department of Geology,
The University,
Leicester, LE1 7RH.

## References

ALLEN, J.R.L. 1965. The sedimentation and palaeogeography of the Old Red Sandstone of Anglesey, North Wales. *Proc. Yorks. Geol. Soc.*, vol.35, pp.139-185.

GREENLY, E. 1919. The geology of Anglesey. *Mem. Geol. Surv. UK*, 2 vols.

SHACKLETON, R.M. 1969. The Precambrian of North Wales. In A. Wood (ed.). *The Precambrian and Lower Palaeozoic Rocks of Wales.* Univ. of Wales Press.

THORPE, R.S. 1972. Ocean floor basalt affinity of Precambrian glaucophane schist from Anglesey. *Nature, Phys. Sci. London*, vol.240, pp.164-166.

WOOD, M. & NICHOLLS, G.D. 1973. Precambrian stromatolytic limestones from northern Anglesey. *Nature, Phys. Sci. London*, vol.241, p.65.

EXCURSION REPORT: STANTON SYNCLINE, DERBYSHIRE

Leader: J.I. Chisholm Sunday, 5th July, 1981

The purpose of the excursion was to examine an example of growth faulting in the Millstone Grit. Growth faulting is a process in which deltaic sediments are affected by slumping during deposition. The resulting body of sandstone is tilted by rotational movement along a curved fault plane, just as in a landslip, and the slump-scar is filled by an extra thickness of sand not present outside the faulted mass.

The party assembled about 10.15 and walked first to a point above Winster (SK 242.602), from where there is an excellent view of the landscape features formed by the normal Millstone Grit sequence, just outside the area affected by faulting. The skyline plateau is Ashover Grit in river-channel facies; below are strong ridges of turbidite sandstone, and beneath these a broad vale formed by basinal mudstones. The dolomitised top of the underlying Carboniferous Limestone was examined close to the viewpoint, at Wyn's Tor.

The next stop was at a quarry (SK 2435.6282) on the top of the plateau of Stanton Moor, where we were able to examine the coarse cross-bedded river channel facies of the Ashover Grit, a typical Millstone Grit lithology formed in this locality after growth faulting had ceased. To the south-west, and at a lower level, lies a marked ridge of sandstone involved in the growth fault structure. The extra thickness of rock deposited in the slump scar is exposed in a quarry (SK 242.624) by the road but blocks of sandstone were being moved about by machinery, so no close inspection could be made. The leader was at pains to point out the unusual thickly bedded nature of the sandstone here, with its depositional dip to the south-east that has resulted from the rotational fault movement.

After lunch the party walked down the length of the ridge, looking at details of the faulted mass. At Rowtor Rocks (SK 235.621) a picturesque spot with steps and seats carved out of the massive grit, the thickly bedded 'extra' rock lies with strongly erosive contact on a cross-bedded sandstone like the one at the top of the plateau. The relationship is well exposed and was looked at in detail. This point lies about 100 metres below the level of the sandstones first examined, so that the sandstone in the faulted mass and above it is at least that thick, whereas the cross-bedded leaf of the Ashover Grit outside the area of faulting is normally less than 60 metres thick.

For a view of the whole structure we walked up a nearby hillside from where the position of the fault can be clearly seen. To the left the downfaulted and thickened sandstone forms the ridge the party had just walked down, and to the right the turbidite sandstones make a gentle dip-slope until cut off by the fault. We then returned by a route as near as possible along the outcrop of the fault plane, and were met by the bus in Birchover.

In what little time remained the leader tried to put the growth faulted area into its context within the Ashover Grit delta. A brief stop was made north of Bakewell (SK 217.701) where the cross-bedded river channel facies of the Ashover Grit has died out, and only turbidites remain. The last stop of the day was above Calver (SK 238.744) from where it is possible to see a small ridge dying out northwards into a featureless slope below Froggatt Edge - the last feather-edge of the Ashover Grit turbidites. From here the party returned to Nottingham.

## References

MAYHEW, R.W. 1967. The Ashover and Chatsworth Grits in north-east Derbyshire. Neves, R. & Downie, C. (eds.), *Geological Excursions in the Sheffield region.* University of Sheffield.

CHISHOLM, J.I. 1977. Growth faulting and sandstone deposition in the Namurian of the Stanton Syncline, Derbyshire. *Proc. Yorks. Geol. Soc.*, vol.41, pp.305-23.

J.I. Chisholm, Inst. of Geological Sciences
Ring Road Halton, Leeds LS15 8TQ

LEHMANN, U. *The ammonites: their life and their world.* Cambridge University Press 1981
Translated from the German by Janine Lettau.
246 pp., 108 text-figs., appendices, index, hard cover, £9.95.

Ammonites in the restricted sense belong to the Mesozoic. If goniatites are to be included, the range can be extended back into the Upper Palaeozoic. The fact that none are living at the present day means that their biology must be gleaned from close living relatives and from the meagre fossil record. The book commences with a class review of the cephalopods and a review of nautiloid morphology. There is, in this introduction, a review also of the mode of fossilisation of cephalopods generally. The introduction occupies some 39 pages. The next 23 deal with fossil cephalopods of which 14 are devoted to ammonites (excluding goniatites). As the subtitle of the book might suggest the bulk of the book is concerned with zoological topics such as ontogeny (life history), sexual dimorphism, locomotion and a review of cephalopod jaws. This section comprises about half the text. The world of the ammonites (? their palaeoecology) is concerned with feeding, predation, pathology and a little about associated organisms. Except for the comment that ammonites lived in a marine environment, the details on associated organisms are rather sparse.

Almost too late (final chapter) the book includes a brief outline on ammonite evolution as a build up to the demise of the group. The usual speculations on this topic will be found neatly summarised. Perhaps the most important part of the book is the section dealing with the origin of aptychii, a favourite subject for the author but appearing for the first time in English. Most text-books consider these objects to be some kind of operculum, concerned with the hood of the animal. Lehmann supports the view with an excellent summary of the evidence, that they are part of the jaw aparatus of the ammonite.

I do not know if the book reads as well in German as it does in English, but the latter must in part at least be due to the fluency of the translator. This book must have a revival of sales now that it appears in English for the first time. Could the book be lengthened a bit for any revision, to include more on the evolution of ammonites and their distribution both in time and space? To anybody wanting to know a great deal about the biology of ammonites, the book must be a winner.

SMITH, A.G., HURLEY, A.M. & BRIDEN, J.C., *Phanerozoic paleocontinental world maps.* Cambridge University Press, Earth Science Series 1981, 102 pp., 88 maps. hard cover, £15.00; paper-back, £6.95

The earlier book of world maps compiled by SMITH, A.G. & BRIDEN, J.C., *Mesozoic and Cenozoic paleocontinental maps*, C.U.P., 1977 has now been superceded by the above title. The earlier work was reviewed in the Mercian Geologist in volume 6, no. 4, 1978, p.312.

The format of the new book is similar to the first, a series of maps mainly at 20 million year intervals from the present day back to the beginning of the Trias. In the new book, the interval then changes to 40 million years and the oldest map is for the early Cambrian, hence Phanerozoic.

The continental outlines as before are represented by the present coastline and by the 1000 m submarine contour. They are presented, however, on different projections from the first book; now they are cylindrical equidistant and Lambert equal area projections. The latter are drawn in North and South Pole views. Certainly one of the points of discussion on this book will be the advantages or otherwise of the use of the cylindrical equidistant projection compared with the Mercator projection chosen for the first book. The polar distortion of this projection is very obvious and renders comparison of amended lines between the two books difficult.

It was stated in the first book that the maps, data and plotting programmes being on computor files, could be updated and reprinted easily but the new projections will have made part of the job more difficult than it need have been. Has the incorporation of new palaeomagnetic data altered the outline of the continents all that much? In the Palaeozoic the land areas are not now represented as complete continents but as segments. The value of this book is the inclusion of these older maps. As for reliability of the results, the arguments for this are clearly put at the start of each section and outline the very great problems that exist for this type of study.

Has the earth remained its present size throughout its history? Has there been contraction or expansion? According to these authors there has not been much change for the last 560 million years; but what about the earlier 4000 million years? Clearly a start in this form of palaeogeography has been made but there is still a long way to go yet.

F.M. Taylor

## LETTERS TO THE EDITOR

5th January 1982

Dear Sir:

"My attention has just been drawn to a paper by D.D.J. Antia entitled "The Temeside Bone Bed and associated sediments from Wales and the Welsh Borderland" published in Mercian Geologist (Vol. 8, No. 3, 1981) which contains an appendix "Pridiolian (sic) marine fossils from the supposedly Lower (sic) Ludfordian (Ludlovian) Cennan (sic) Beds of the Cennan (sic) Valley" (Appendix 2, p. 207). In this appendix my name appears as first author. I wish to make it quite clear that this is the first time I have seen the article in its present form. I wish to disassociate myself completely from it. This appendix contains numerous factual and spelling errors.

The object of this so-called supplementary study was not to demonstrate that the Cennen (note correct spelling) Beds were of one age rather than another; it was a conclusion that Dr. Antia came to after I drew his attention to a sample I had collected as part of my PhD work. I accepted his fossil identifications and their implied age for these sediments in good faith.

The published paper is virtually identical to a manuscript rejected by the Geological Magazine. I accepted the criticisms that were levelled at this document regarding the questionability of the identifications and their apparent age. When I attempted to check the identifications I was told by the then Mr. Antia that he could not find the specimens! I naturally considered the matter closed. You can therefore imagine my amazement and outrage that he has resurrected this erroneous and misleading manuscript and appended it to his paper with my name still attached! I am even more amazed that no one on the staff of the Mercian Geologist sent me proofs or even a copy of the paper prior to publication as I am listed as first author. If this had been done I would have objected to it being published with my name attached.

I demand this letter be published in the Mercian Geologist, with an appropriate apology, at the earliest opportunity. Otherwise I will be forced to take legal action to protect my professional reputation."

Yours faithfully,

Dr. David R. Atkins
Exploration Division
The British National Oil Corporation
150 St. Vincent Street
GLASGOW

### Reference

ATKINS, D.R. & ANTIA, D.D.J. 1981. Appendix 2, p. 207, in: Antia, D.D.J., 1981. The Temeside Bone Bed and associated sediments from Wales and the Welsh Borderland. *Mercian Geol.*, Vol. 8, Pt. 2, pp. 163-215.

23rd December 1981

Dear Sir:

"D.D.J. Antia, in a recent paper "The Temeside Bone-Bed and associated sediments from Wales and the Welsh Borderland" published in Mercian Geologist (Vol. 8, no.3, 1981), included an appendix written jointly with D.R. Atkins entitled "Pridiolian [*sic*] marine fossils from the supposedly Lower [*sic*] Ludfordian (Ludlovian) Cennan [*sic*] Beds of the Cennan [*sic*] Valley" (Appendix 2, p. 207). They claim to have collected an ostracod assemblage consisting of *Frostiella groenvalliana* Martinsson, ?*Frostiella*, *F.* cf. *bicristata* Shaw, *Londinia kiesowi* (Krause), *Hermannia* [*sic*] cf. *marginata* (Jones) [*sic*] and ?*Nyhamnella* sp. from the Cennan [*sic*] Beds which proves a Downtonian (Pridiolian) [*sic*] age, not Upper [*sic*] Leintwardinian (Lr. [*sic*] Ludfordian) as suggested by us (Squirrell and White 1978). According to Antia and Atkins, the collection was obtained from a road cutting (NGR SN 6102 1906), 4km south-west of Llandeilo, Dyfed, about 0.56m above the base of the unit.

The National Grid Reference confirms that Atkins and Antia are referring to the Cennen Beds of our account. During our investigations we made large collections from the Cennen Beds, and details of the fauna are listed in our published account (Table 3, p. 8). *F. groenvalliana* or a closely related form is common, a species which hitherto has been recorded solely from the Downton Series. However, the evidence and reasons for concluding that the Cennen Beds represent an extremely attenuated sequence of late Leintwardinian and possibly Whitcliffian age (i.e. mid- to late Ludfordian, following Holland, Lawson, Walmsley and White 1980) are fully discussed (pp. 8, 9, 14, 15). Earlier, Potter and Price (1965) had also concluded that these strata represent an attenuated late Ludlow sequence.

Subsequent to the publication of our account, Dr. R. Turner, formerly of IGS Leeds, reported to us that from a sample taken at 1.3 m above the base of the Cennen Beds he had obtained a "moderately abundant assemblage of reasonably well preserved acritarchs" which "clearly indicates a Ludlovian age for the sample" and that a Whitcliffian age is most probable. Recently, Mr. K. Dorning, Pallab Research, Sheffield, informed us that a sample he investigated from the Cennen Beds indicates an age equivalent to that of the Upper Leintwardine Beds or low Lower Whitcliffe Beds of the Ludlow area, Shropshire.

Atkins' and Antia's publication is both misleading and unscientific, since no reference is made to the information given in our paper, nor to our reasons for regarding the Cennen Beds as being of late Ludlow rather than Downton age, a decision supported by the micro-fossil evidence, as mentioned above. Furthermore, their records of typical Downton Series ostracods not found in our collections cannot now be substantiated, because we have been informed that their collection has been lost. In the circumstances, we see no reason for changing our published interpretation of the age of these strata.

We do not wish to embarrass you further by listing all the errors in the poorly presented Appendix 2 of Antia's publication. May we also point out that absence of comment here on other parts of the paper should not be taken to imply that we accept any of it?"

H.C. Squirrell
D.E. White
Institute of Geological Sciences
Exhibition Road
London SW7 2DE

References

ATKINS, D.R. & ANTIA, D.D.J. 1981. Appendix 2, p. 207, in: Antia, D.D.J., 1981. The Temeside Bone-Bed and associated sediments from Wales and the Welsh Borderland. *Mercian Geol.*, Vol. 8, Pt. 2, pp.163-215.

HOLLAND, C.H., LAWSON, J.D., WALMSLEY, V.G., & WHITE, D.E. 1980. Ludlow Stages. *Lethaia*, Vol. 13, p. 268.

POTTER, J.F., & PRICE, J.H. 1965. Comparative sections through rocks of Ludlovian-Downtonian age in the Llandovery and Llandeilo districts. *Proc. Geol. Assoc.*, Vol. 76, Pt. 4, pp.379-402.

SQUIRRELL, H.C. & WHITE, D.E. 1978. Stratigraphy of the Silurian and Old Red Sandstone of the Cennen Valley and adjacent areas, south-east Dyfed, Wales. *Rep. Inst. Geol. Sci.*, No. 78/6.

29th December 1981

Dear Sir:

"The long paper by D.D.J. Antia in the Mercian Geologist vol.8 no. 3 (1981) is on the important subject of the Temeside Bone-Bed and the associated sediments. It is therefore likely to be taken seriously, particularly by readers overseas. Although I am familiar with both the rocks and the region concerned I find parts of the paper very confusing and I imagine many geologists abroad will be even more confused. I will restrict my criticism to the following nine points.

1. The numerous spelling errors (e.g. Cennan for Cennen, *Lerpiditia* for *Leperditia*, *Leodispis* for *Ledopsis*, *N. sissica* for *N. scissa*, *Aegeria* for *Aegiria*, etc.) might be considered as irritatingly careless rather than misleading but it is deplorable that the important series name Pridoli (more correctly Přídolí) is misspelt throughout as Pridioli - particularly as I corrected this error in the early draft of the paper.

2. More serious, especially for overseas visitors, are the incorrect map references, particularly where they are not accompanied by an adequate description or map of the locality. For instance, Onibury is 8 km. N.W. of the given map reference SO 520.742 and Ludlow railway cutting is 6 km. W. of SO 574.748 (both on p. 165). On p. 166 there is a full-page diagram vaguely located as "Downton" with a map reference of SO 456.742, indicating a position in the fields about 1 km. E. of the well-known Downton Castle Bridge localities.

3. Even more serious is the assertion by Antia (p.168, para. 1) that the occurrence of *Ozarkodina remscheidensis* in the Temeside Bone-Bed indicates the position of the Silurian-Devonian boundary in the Welsh Borderlands. The use of the phrase "earliest known occurrence" implies that there are later occurrences of this species in the region but I have not seen them reported. I understand, however, that Antia's record of this important conodont species is based on a single element only, a fact not stated by him in his papers. I also understand, from discussions with several Silurian-Devonian conodont experts, that this find, in isolation, has little or no value in locating the base of the Devonian in Britain. I recall warning Dr. Antia that his discovery was not as significant as he (and I) first hoped but this has evidently failed to deter him from postulating a correlation inadequately supported by the evidence.

4. In para. 2 on p.168, Antia correctly points to the international popularity of the name Pridoli for the fourth series of the Silurian but is incorrect in assuming that the name Downton is no longer a contender for this honour. There has recently been increasing support abroad for the use of this classic British term and the Subcommission on Silurian Stratigraphy is presently receiving and considering submissions on the names Downton, Pridoli and Skala before a decision is made on the nomenclature and stratotypes for the fourth series of the Silurian System. I should have thought that Dr. Antia was well aware of these activities, either from a circular which he received from me or by careful reading of one of the references listed in his paper i.e. Holland 1980, p.238, line 29.

5. Referring to para. 4 on p.168 of Antia's paper, it should perhaps be made clear that the decision to reduce the Ludlow stages from four to two was taken by the Silurian Subcommission and not by Holland, Lawson, Walmsley and White. Their main function was to propose suitable names for the two new stages. The overriding consideration in the decision by the Subcommission was the potential of these two stages for international usage as their bases correspond very closely to the bases of the widespread graptolite zones of *Neodiversograptus nilssoni* and *Saetograptus leintwardinensis* respectively.

6. On p.169, para. 5, Antia states that it has been shown conclusively by Kaljo that the base of the Pridoli Series extends into the topmost Ludlovian. This is far too dogmatic a statement. A paper in press on "The Downton Series as the fourth Series of the Silurian System" by Bassett, Lawson and White includes a chapter on international correlation compiled with the assistance of Dr. Kaljo himself plus Professor Martinsson (ostracodes) and Dr. Teller (graptolites). The detailed discussion of the palaeontological evidence now suggests that the bases of the Downton and Pridoli Series may, after all, be of approximately the same age. Even if Kaljo's 1978 correlation is correct, Antia's proposed restriction of the term Ludfordian to exclude the highest Ludlow strata is not justified because the Pridoli has not been internationally approved as the name of the fourth series. Indeed, one strong argument in favour of the use of the term Downton is that its adoption would preserve the long-established scope of the internationally recognised Ludlow Series.

7. Para. 6 on p.169 and Table 1 in Antia's paper present a new and "clarified" lithostratigraphy for the upper part of the Ludlow Series. Holland *et al.* (1963) established 9 mappable subdivisions of the Ludlow rocks which have stood the test of time. Only very recently (Holland *et al.* 1980), these divisions were given the designation "Formation" instead of "Beds". Antia retains these units as members and introduces new formation and group names. His scheme is logical and his names attractive and appropriate; his reason for grouping the Lower and Upper Whitcliffe Beds into the same formation is a good one - except that on these grounds perhaps the lithologically similar Lower and Upper Leintwardine Beds should also be included. Nevertheless, it seems irresponsible and confusing to introduce a rival classification so soon after a long-standing scheme has been up-dated and ratified, unless it can be demonstrated that the present classification results in serious inconvenience.

8. The most confusing part (to me) of Antia's Temeside tale comes on p.172, where he states that the Temeside Formation appears to be absent at Downton - contrary to "a widely held belief". Elles & Slater, the founders of the Temeside Shales, stated clearly (1906, p.199) that "The Temeside Group, as its name denotes, is well exposed along the banks of the Teme, both at Ludlow and in the neighbourhood of Downton Castle; it comprises beds which are virtually passage-beds into the Old Red Sandstone, and may be subdivided into the Downton-Castle or Yellow Sandstones below, and the Temeside Shales above." The name Temeside Shales or Formation is in general use for the predominantly olive-green sediments between the yellowish Downton Castle Sandstone Formation and the mainly red Ledbury Formation: the Temeside Bone-Bed is the name given to the most prominent bone-bed in that formation. It thus comes as a shock to see that Antia in his Text-fig. 4 (p.173) places what is virtually Elles & Slater's type section for their Temeside Shales and Temeside Bone-Bed into the Ledbury Formation, especially as he agrees on the grey and olive-green colours of the sediments. Perhaps the presence of red clays and silts below the green strata persuaded (or misled) him, but surely some explanation and discussion is called for? As for the Downton area, Elles & Slater (pp.211-214) clearly describe typical Temeside Shales at several localities, presumably not visited by Antia. Temeside Shales have also been seen at Downton (not merely "believed in", to quote Antia's quaint terminology) by Holland *et al.* (1963, p.135), Whitaker (1962, p.338), Allen (1974, p.133, fig.24) and many other geologists including myself. Another curious statement by Antia is that King & Lewis's (1912) canal sections in the Birmingham area are no longer accessible. The Brewin's Bridge canal section near Netherton was well exposed and easily accessible in 1974. Has Dr. Antia personally visited this locality and, if so, what has happened to make it inaccessible? The same question may be put about the section near Ludlow station as I presume the railway cutting still exists but perhaps the section is overgrown?

9. As I am mentioned in the Acknowledgements (p.201) as having read all or part of the manuscript I hasten to make it clear that I read it only in its thesis form and that I made some major criticisms which have been ignored in this subsequent paper. Many of the other items which I find confusing have been added at a later stage.

In conclusion, I must stress that this paper contains much potentially valuable data and some significant conclusions. The presence of such inaccurate or inadequate statements as I have criticised above is therefore doubly unfortunate as the reader is liable to lose faith in those parts of the paper which he is less competent to assess. I now find myself asking such questions as: How reliable is the sedimentology? Are the fossil identifications correct? Did Dr. Antia really collect and count 305,008 plant fragments (p.167)? Is there really such a fossil as *Hypermania* sp. (p.199) or is this a Freudian slip?"

Yours sincerely,

J.D. Lawson
Dept. of Geology
University
Glasgow G12 8QQ

References

ANTIA, D.D.J. 1981. The Temeside Bone-Bed and associated sediments from Wales and the Welsh Borderland. *Mercian Geol.*, vol.8, pp.163-215.

ELLES, G.L. & SLATER, I.L. 1906. The highest Silurian rocks of the Ludlow District. *Q. Jl. geol. Soc. Lond.*, vol.62, pp.195-222.

HOLLAND, C.H. 1980. Silurian Series and Stages: decisions concerning chronostratigraphy. *Lethaia*, vol.13, p.238.

HOLLAND, C.H., LAWSON, J.D. & WALMSLEY, V.G. 1963. The Silurian rocks of the Ludlow District, Shropshire. *Bull. Br. Mus. (Nat. Hist.) Geol.*, vol.8, pp.95-171.

HOLLAND, C.H., LAWSON, J.D., WALMSLEY, V.G. & WHITE, D.E. 1980. Ludlow Stages. *Lethaia*, vol.13, p.268.

## Corrections

The following corrections should be made in D.D.J. Antia's paper: The Temeside Bone-bed and associated sediments from Wales and the Welsh Borderland, published in the last issue of the Mercian Geologist, vol.8, no.3, pp.163-216.

| | | |
|---|---|---|
| Cennan | should read | Cennen. Summary p.163, pp. 168, 201, 207. |
| Pridioli | " " | Pridoli. pp. 163, 168, 169, 170, 171, 207. |
| *Lerpiditia* | " " | *Leperditia.* p.165. |
| *Leodispis* | " " | *Ledopsis.* pp. 175, 190, 193, 194, 198. |
| *N. sissica* | " " | *N. scissa.* p.199. |
| *Aegeria* | " " | *Aegiria.* p.198. |
| SO 520742 | " " | SO 455794. p.165, as on p.182, which is correct. |
| SO 574748 | " " | SO 514748. p.165. |
| *Hypermania* | " " | *Hyperamnia.* p.199. |

## Apology

The above errors are referred to in the letters on the previous pages. In addition to these points, Dr. Atkins implies that proofs of Appendix 2, should have been sent to him by the Editor. All the correspondence for the Antia paper, which includes the appendix referred to, was carried out with Dr. Antia, who submitted the complete manuscript in the first instance and received referees and editorial comments and in due page proofs. As the article was lengthy (53 pages), and alterations numerous, two sets of proofs were looked at by Dr. Antia. The appendix, consisting of 1 page (p.207), was included with the rest of the proofs. I assumed that Dr. Antia would have contacted his co-author for that page and he assumed I sent one to Dr. Atkins direct. I very much regret that Dr. Atkins did not, in fact, see either proof copy. The only address we had for Dr. Atkins was that given at the top of p.207. Nevertheless I accept Dr. Atkins' point; I should have insisted that the relevant page at least was forwarded to Dr. Atkins. Even if he had withdrawn as author (part) from the appendix as a consequence, he would have corrected a large proportion of the spelling errors noted above.

We hereby publish the apology demanded by Dr. Atkins and very much regret that he did not see the page referred to before publication.

A reply to all correspondence has been received from Dr. Antia. Unfortunately, proof pages have not been prepared in time for this issue. They will appear in the next issue, vol.9, no.1. Further delay would have meant that vol.8, no.4 would not have been published until September.

F.M. Taylor,
Editor.

## Index for Volume 8, 1981-1982

A



B



C

D



E



F

L



M



N

T



U



V



W



Y

## SOLUTION TO CROSSWORD PUZZLE NO. 1

### Across

1. Generic   5. *Peltura*   8. Ash   9. *Atops*   10. Antenna

12. Sonic   13. Gene   15. Rig   16. Plicate   18. Ems

20. *Lichas*   21 & 35. Facial sutures   23. I.G.S.

25. Andorra   26. Tea   27. Side   30. Eight   32. Tangent

33. *Ampyx*   34. Urn   36. *Asaphus*

### Down

1. Gray   2. *Niobe*   3. *Resseria*   4. Carnage

5. *Phacops*   6. Lath   7. *Asaphellus*   11. *Nevadia*

14. *Dalmanites*   17. Acadian   19. Mug   22. *Acastava*

23. Iapetus   24. *Stygina*   28. Depth   29. Rear

31. Axis

## THE MERCIAN GEOLOGIST

### Journal of the East Midlands Geological Society

The journal first appeared in December 1964 and since that time 32 parts, comprising 8 volumes have been issued; the last, Vol. 8, No. 3 in Nov., 1981. The Mercian Geologist publishes articles especially on the geology of the Midlands of England, but other articles have been published which are of current interest to geology generally. Contents include original papers, review articles, biography, bibliographies, excursion reports, book reviews and the Secretary's report on Society activities.

For Contributors:

Authors intending to submit manuscripts of papers for publication in the Mercian Geologist are asked to follow the format of papers included in a recent number of the journal, and if possible to provide two copies. As the journal is read by Members with a wide spectrum of geological interest and ability, authors are asked to ensure adequate introductions for their papers, particularly, if the subject has not been reviewed in the journal over the last few years. The paper should be complete in itself, without the need of the reader to refer to specialist journals not easily available to the average Member of this Society. It follows that the length of the paper may be greater than that published by some other journals but authors are asked to be as lucid and concise as possible and to avoid repetition.

Text-figs. normally occupy a full page of the journal, but part diagrams can be fitted into the typed page. Double page diagrams have been published with a single fold but each printed page has to be folded by hand. The standard reduction by our present printing process is approximately x 0.75. Thus the optimum size for the original diagram, including space for caption, index and explanation if required on the diagram, should be 285 x 190 mm. (285 x 380 mm with a single fold). Greater reduction is possible but care must be taken with the original to ensure that at the final reduced size (230 x 155 mm; or 230 x 310 mm) the smallest letters are no smaller than 1 mm and that there is a similar minimum spacing between letters and lines. Bar scales (metric) should be provided as the exact reduction cannot be guaranteed.

Half-tone plates are reproduced at the original size, and should not exceed 230 x 155 mm. The quality of the published photograph depends initially on the quality of the original and it follows that the photographs submitted should be exactly as the author would wish them to appear in the journal - good contrast, in focus, adequate magnification and without distortion.

If there are any points of difficulty, please do not hesitate to contact the editor during the production of the manuscript. The Editor's sole concern is to produce excellent quality papers to be enjoyed by all readers. Please send completed manuscripts to the editor.

For Readers:

All parts of the journal are available for purchase and a detailed contents list will be sent on request. Current numbers of the journal are usually obtained by subscription: [32 parts issued in 18 years].

1982

| | | | |
|---|---|---|---|
| Ordinary Members | £6.00 | Joint Member | £6.25 |
| Institutional Members | £6.00 | | |

Single copies £3.50 (£3.00 Institutional Members; Other Members £2.50)
Complete volumes, 4 parts; £13.00 (£12.00 Institutions; Other Members £10.00).

Librarians in overseas libraries and geological institutions may take part in an exchange scheme organised by the Science Library of the University of Nottingham. About 200 institutions throughout the world receive the Mercian Geologist by sending in exchange, original geological periodicals.

Address: Editorial matters, manuscripts, exchanges, orders for back numbers

The Editor, Mercian Geologist, Department of Geology,
The University, Nottingham, NG7 2RD, England.

CONTENTS



Issued separately. Cummulative contents and title pages for volume 8.

Mercian Geologist, vol. 8, no. 4, 1982, pp. 241-323, plates 8-11.