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

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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.

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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.

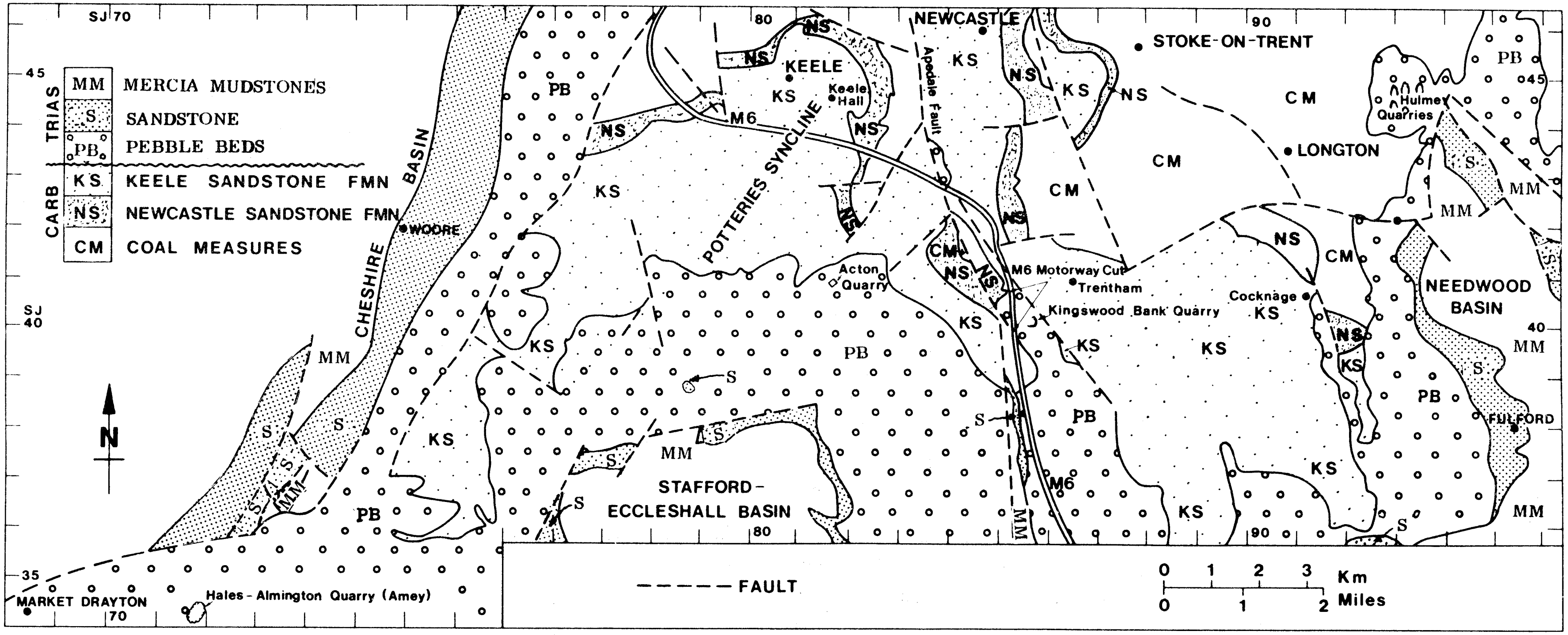
In the present area, the rocks outcrop at the northern ends of the Stafford-Eccleshall and Needwood Basins (text-fig. 1) in a region which was severely faulted during the Permian and in post-Triassic times. In the Trentham area, the M6 Motorway was constructed to take advantage of a natural north-south 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	Stages	Groups	C. New nomenclature in north-central Staffordshire 1980–			
				Warrington *et al.*, 1980, Fig. 2 Area 10. Table 4, Column 10		Warrington *et al.*, 1980, Fig. 2 Area 11. Table 4, Column 11	
				West Cheshire Basin	Stafford-Eccleshall Basin		East Needwood Basin
				Hales-Almington-Lordsley-Maer-Acton-Trentham			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	? Scythian	Sherwood Sandstone Group	? Hardegsen		disconformity ?	
f^3 Bunter Upper Mottled Sandstone	Medium-fine argillaceous sandstone formation			Wilmslow Sandstone Formation	no members recognised	Cannock Chase Formation	b un-named sandstone member
f^2 Bunter Pebble Beds	Pebble bed formation c Pebbly sandstone mbr. b Conglomerate member 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 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

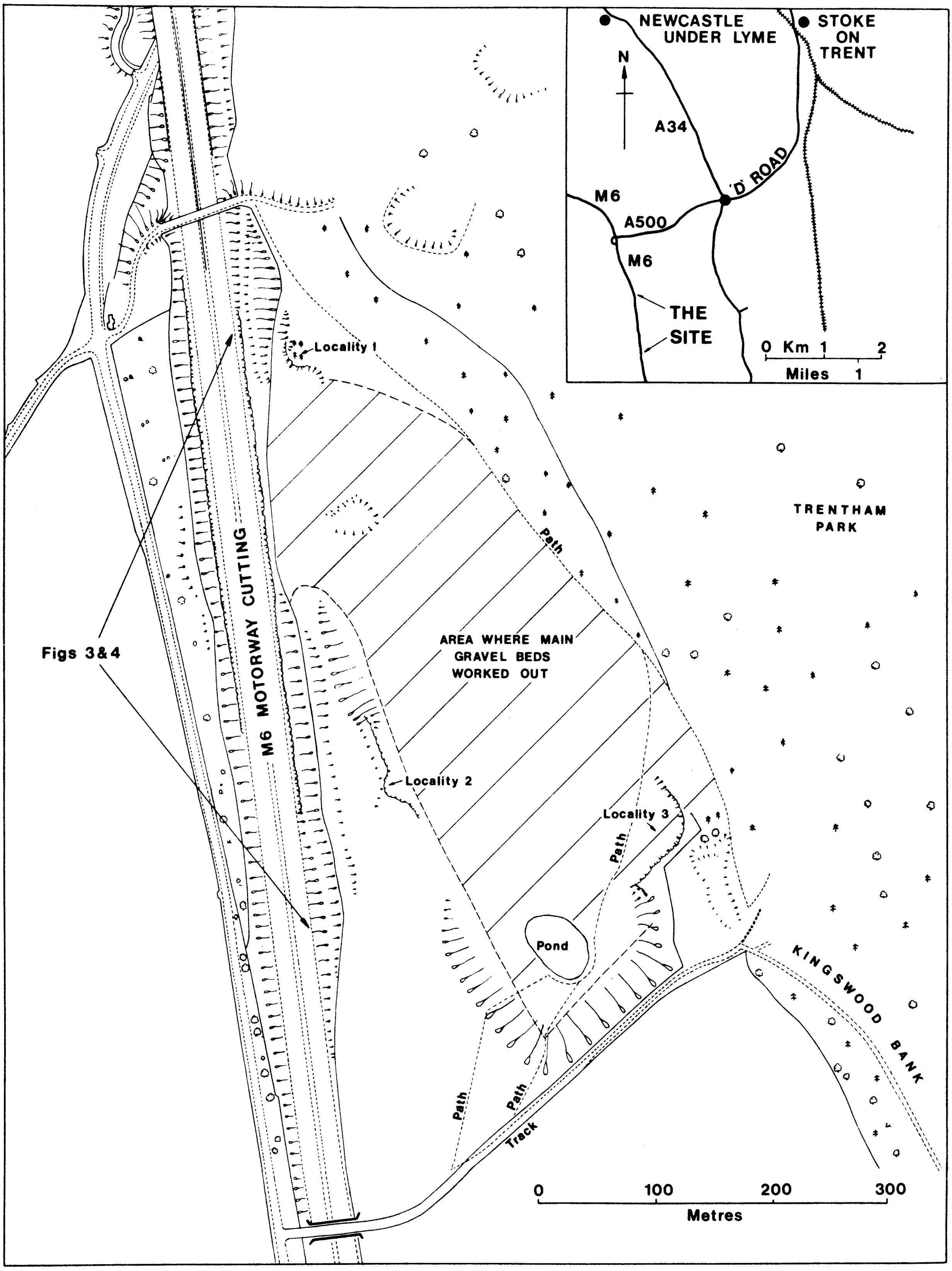
Geotectonic setting. Recently the geotectonic context of the origin of the basins in which the pebble beds were deposited has become clearer (McLean, 1978; Ziegler, 1981). The Cheshire and Worcester grabens originated from the collapse of the northern foreland of the Variscides sometime after the final 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.

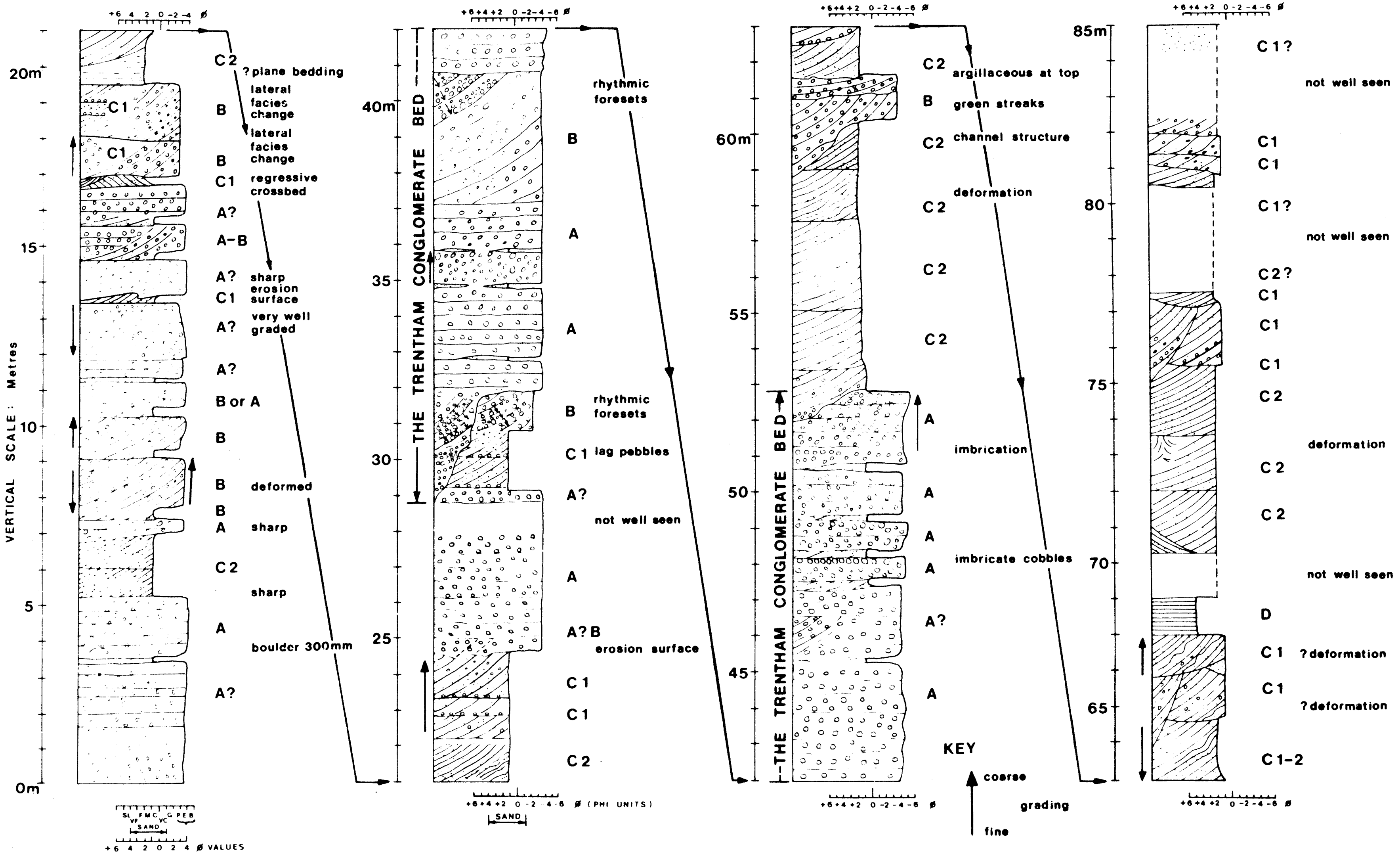
Outline description of the facies and petrography of the pebble beds in relation to highway schemes. Studies initiated after 1971 have demonstrated that the pebble beds consist of several major facies, four of which are specified here only in that detail which relates to their recognition and understanding 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.

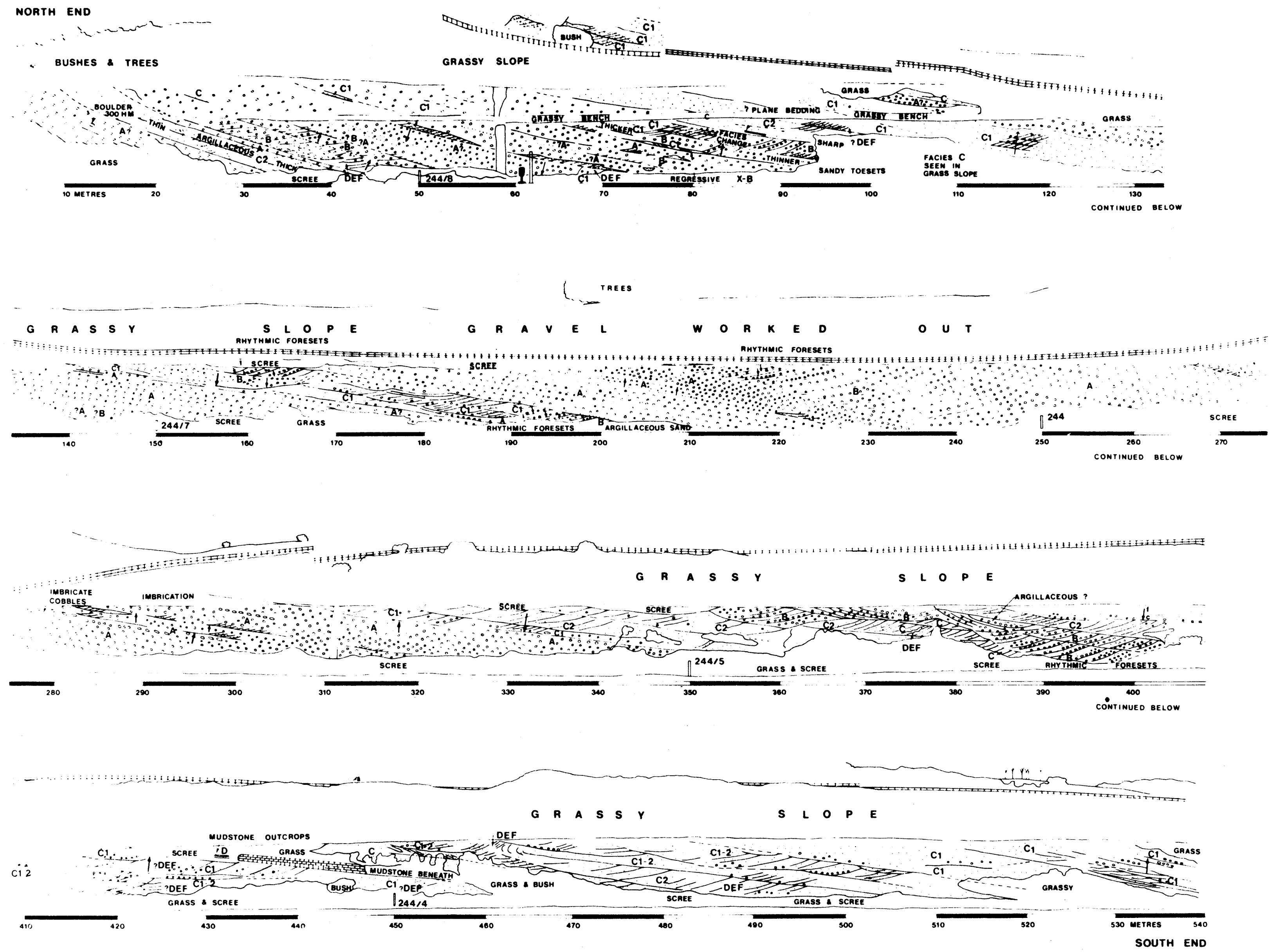
Facies A consists of flat-stratified clast-supported (often openwork) and matrix-supported pebbly conglomerate or gravel organised in units up to 10 m thick. The clasts range from boulders to fine sand, the grain size distribution being bimodal (text-fig. 5). One mode lies in the pebble grade, the other 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



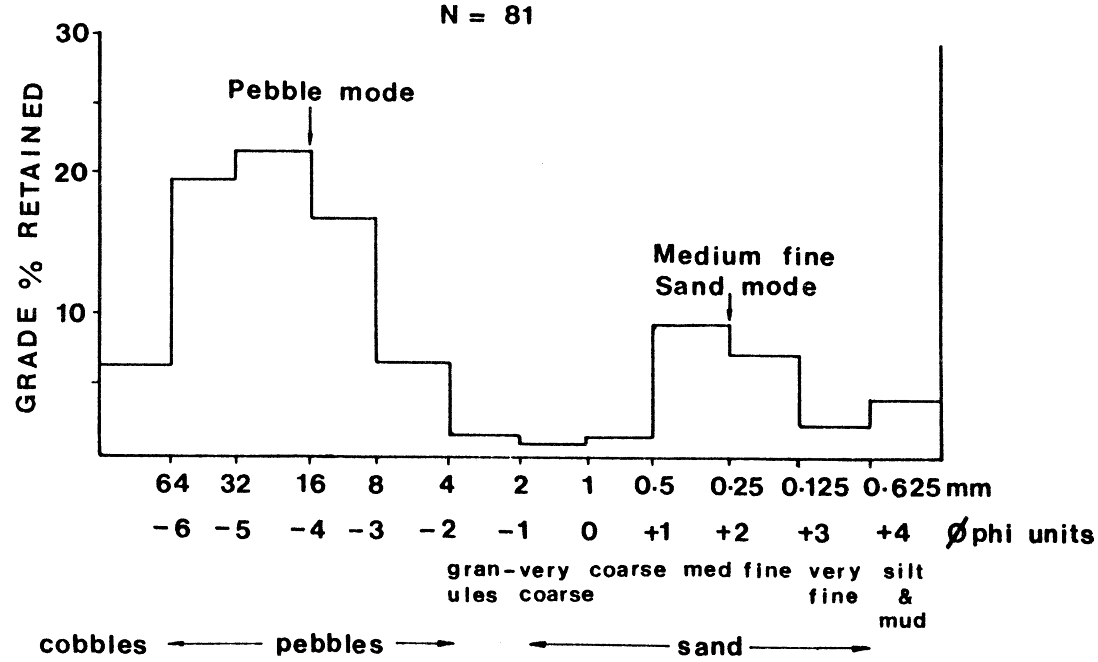
Text-fig. 2: The location of the M6 motorway cuttings and other localities near Kingswood Bank and Trentham Park.



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') The grain-size distribution of Facies A and B shows only a small proportion of fine particles less than $\frac{1}{4}$mm ($+2\phi$: 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 4ϕ), 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 bridgeworks (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.

Plate 8.

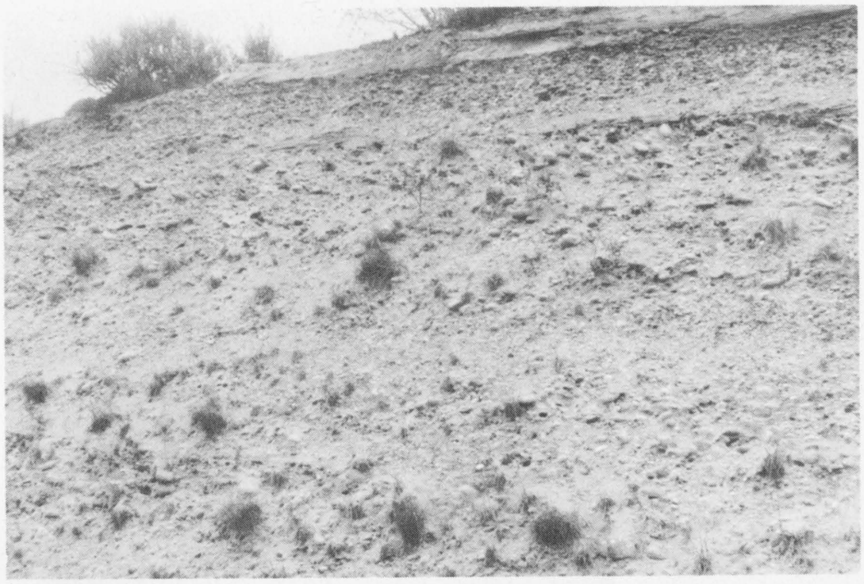


Fig. a

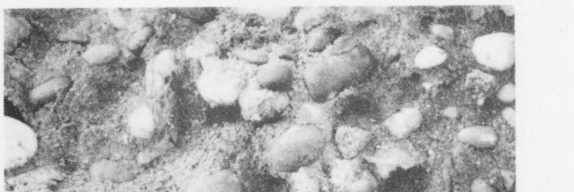


Fig. b

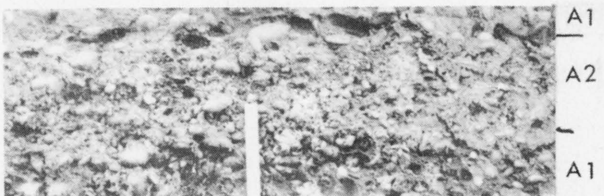


Fig. c

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

Plate 10.

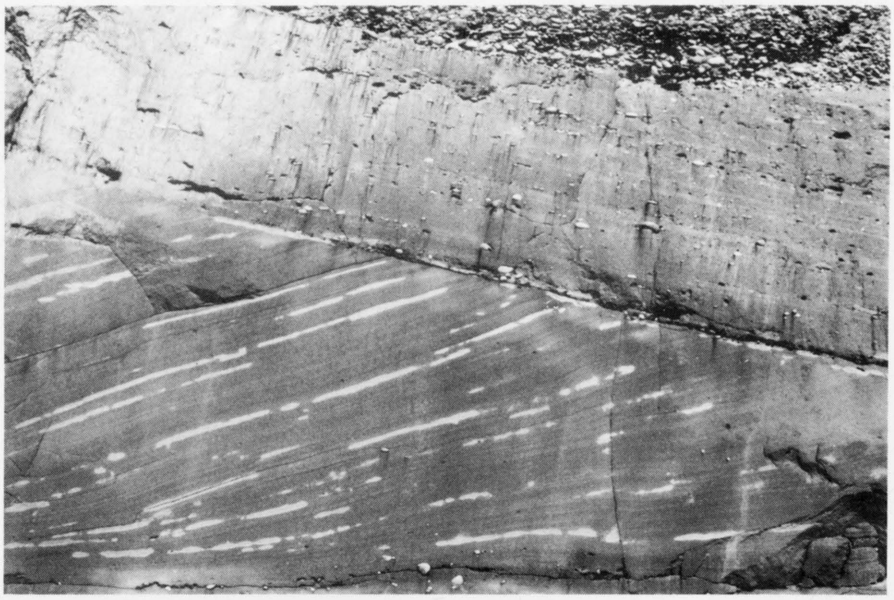


Fig. a

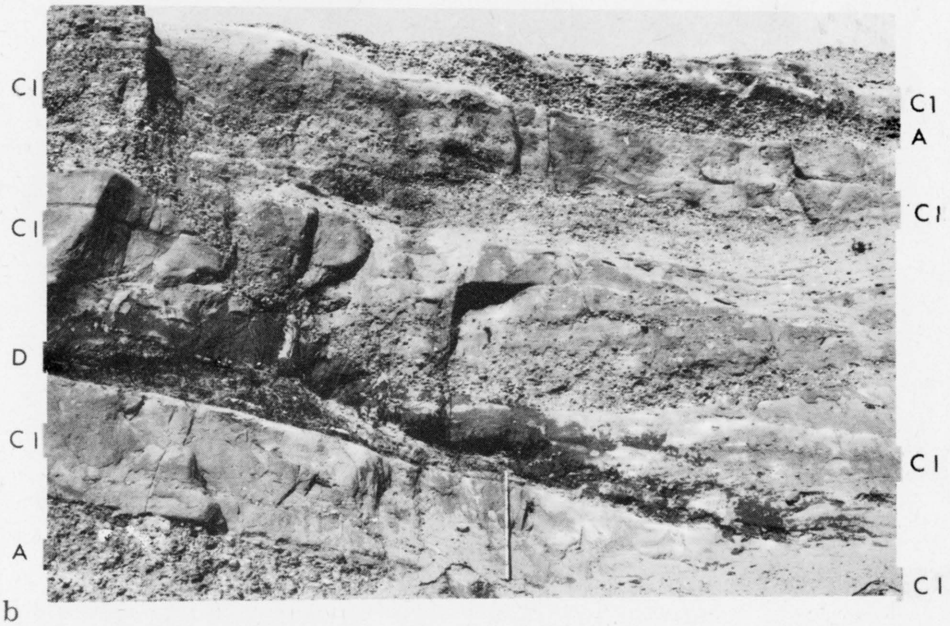


Fig. b

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.

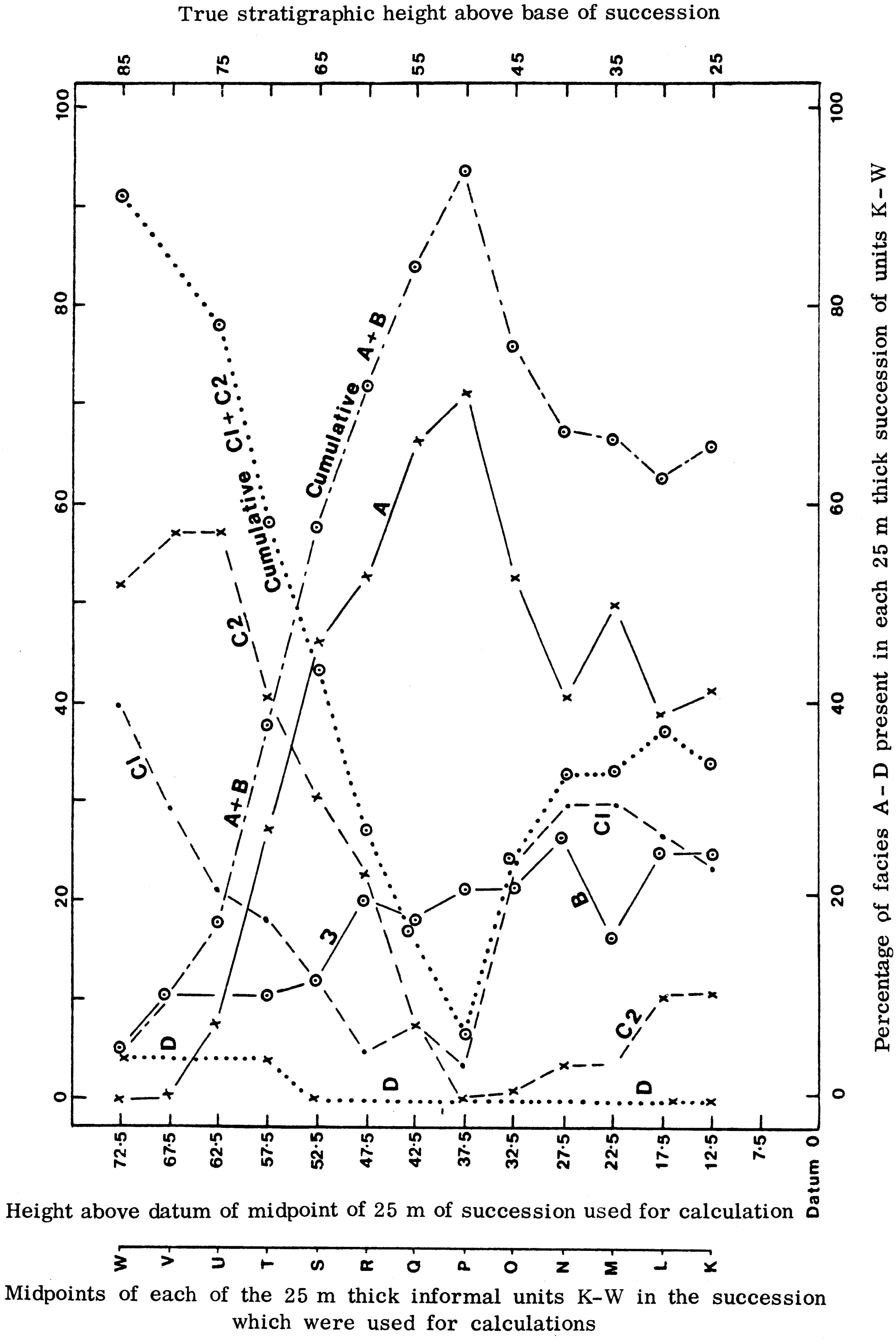
Facies unit	A (%)	B (%)	C1 (%)	C2 (%)	D (%)	gravel and conglomerate A + B (%)	sandstone C1 + C2 (%)
Top of succession: 55-80 m above datum	0.00	10.20	29.40	56.40	4.0	10.20	85.80
Middle of succession: 30-55 m above datum	66.40	18.00	7.60	8.00	0.00	84.40	15.60
Base of succession: 5-30 m above datum	37.80	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.

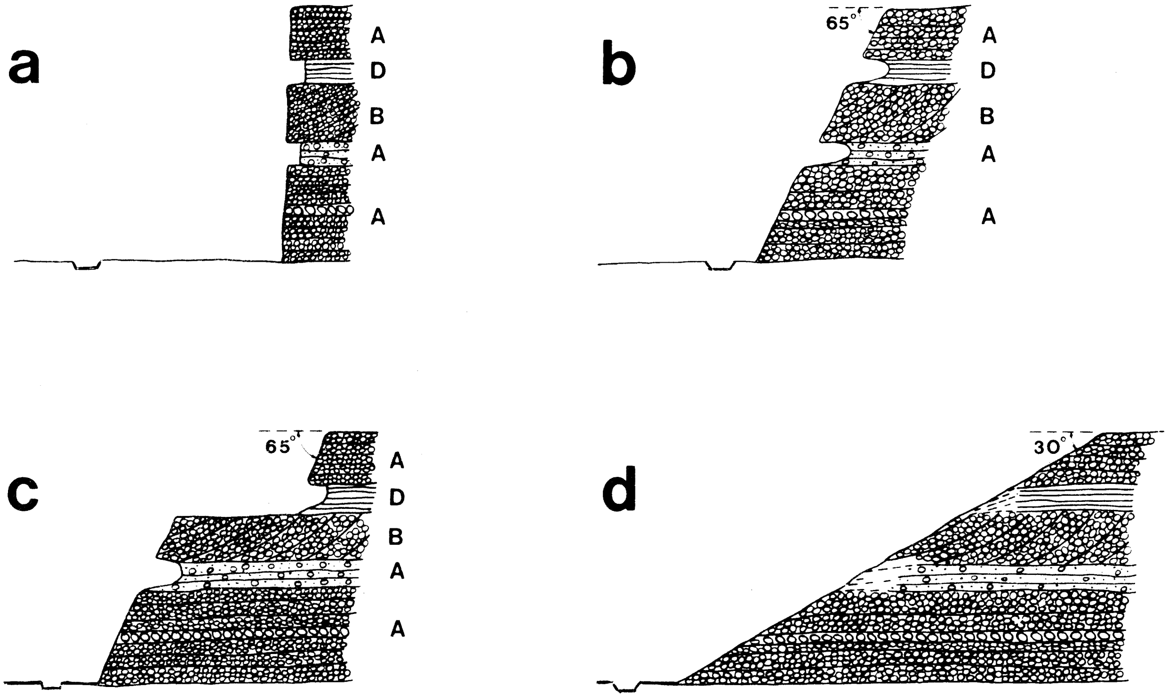
Down-the-hole photography. This has been perfected and used extensively at Hales Almington quarry (Rae, 1976). The succession has been proved there, using a RB 27 RT percussion rig to drill rough 200-225 mm diameter holes at a rate of 3-4.5 m per hour, falling to a 2 m per hour in quartzose conglomerate, 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.

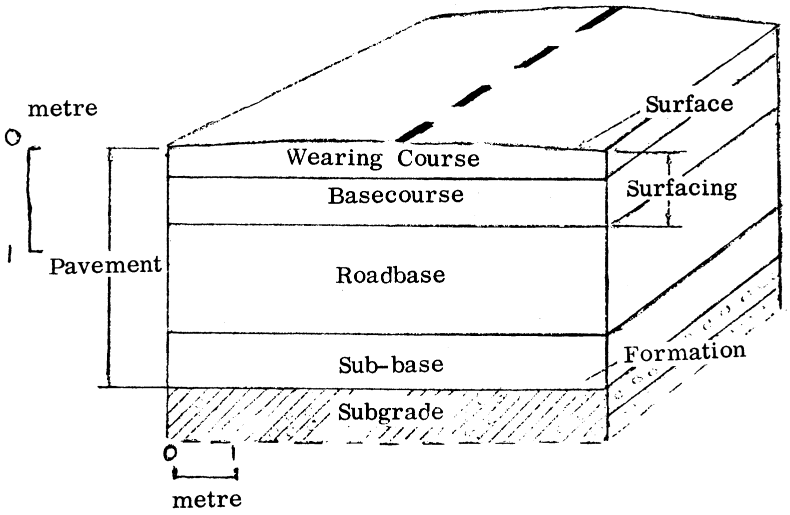
Problems of the exploitation of the pebble beds as material for highway construction

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 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 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.

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