TECHNICAL REPORT WA/89/29

Geology of the Coventry area

Description of 1:25 000 Sheets SP 27/37 and 28/38
(excluding SP 38 NE)

R A Old, D Mc C Bridge and J G Rees

BRITISH GEOLOGICAL SURVEY

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Onshore Geology Series

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Cover illustration

Coventry city centre viewed from the south-west. (*Photo courtesy of Coventry City Council*)

Geographical index

UK, central England, Warwickshire

Subject index

Geology, mineral resources, hydrogeology, engineering geology, planning, thematic maps

Production of this report was funded by the Department of the Environment, but the views expressed in it are not necessarily those of the Department

Maps and diagrams in this report use topography based on Ordnance Survey mapping

Bibliographic reference

Old, R A, Bridge, D McC, and Rees, J G. 1990. Geology of the Coventry area. *British Geological Survey Technical Report* WA/89/29.

Keyworth, Nottingham British Geological Survey **1990**

BRITISH GEOLOGICAL SURVEY

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PREFACE

This report describes aspects of the geology, and includes a set of thematic geology maps, for the area around Coventry (Figure 1) covered by parts of Geological Survey 1:50 000 sheets 168 (Birmingham), 169 (Coventry), 183 (Redditch) and 184 (Warwick). Accounts of the geology of these sheets are given by Eastwood and others (1925 and 1923), and Old and others (in preparation and 1987) respectively.

The present study, which was commissioned and partly funded by the Department of the Environment, was concerned with geological mapping and data collection. These activities resulted in geological maps and reports, and thematic geological maps.

The mapping was carried out by D McC Bridge, R A Old, J G Rees and M G Sumbler in 1977-80 and 1986-88. The geotechnical data were analysed by P R N Hobbs and assistance in the production of the thematic maps was given by J R A Giles, K A Holmes and Miss K M Bardell. Palaeontological contributions were made by Drs N J Riley and A W A Rushton. The nominated officers were Dr B R Marker for the Department of the Environment and Dr R A Old for the British Geological Survey.

The cooperation of local authorities and other holders of data is gratefully acknowledged : a list of the principal data sources is given in Appendix IV. In particular we thank British Coal, Coventry City Council and Nuneaton and Bedworth District Council for the provision of data. Mr E L Parry of the National Rivers Authority provided information on hydrogeology within the study area, and Mr J M Boldon of Aspinwall & Co. Ltd. was an advisor on planning matters.

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April 1990

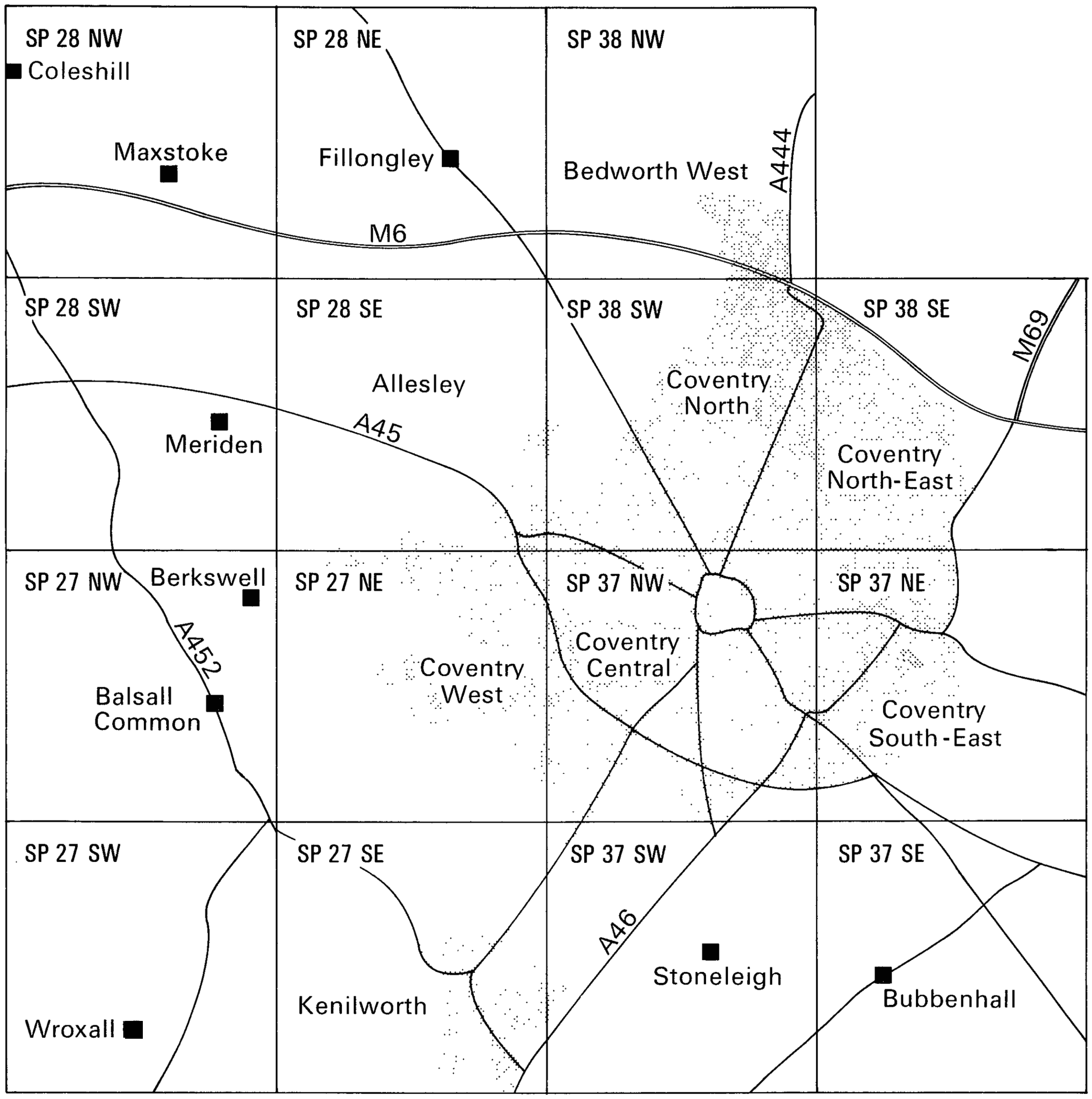

Figure 1. The Study Area and its component 1:10 000 maps

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Notes to the user

This report is divided into two main sections. The first describes the study area, and provides selected geological data and related information in a set of applied themes. It is presented in a style which is intended to be comprehensible to those involved in planning and development, and requires only a little geological knowledge. Seven pairs of thematic maps are included with the report. The second section comprises appendices containing a detailed description of the geology of the area, and sources of data. These are intended primarily for use by those with specialised geological knowledge.

There is considerable variation in the quality and reliability of the source data used to compile this report and the accompanying set of thematic geology maps, as well as a great disparity in the density of site investigation data within the study area. Therefore, the accuracy and reliability of the interpreted information reflects that of the source data. However, emphasis has been placed throughout on the most reliable data, particularly those derived from authoritative sources such as geotechnical engineers and geologists. No information made available after May 1989 has been used in this report. Thus the report and maps are to be regarded as the *best interpretation of the information available at the time of compilation. They should be used for preliminary studies only and are not intended as a substitute for on-site investigations or detailed local searches.* The responsibility for assuring that geological, geotechnical and mineral resource data for any given site are as indicated on the maps, and in the figures and text of this report, must remain solely that of the user.

The possible occurrence of undetected anomalous site conditions should always be anticipated. The indicated occurrences of mineral deposits do not necessarily imply an economic resource. The possible presence of unmapped superficial deposits and made ground of variable thickness, particularly within the urban area of Coventry, should also be taken into account when formulating any development proposals.

There is no substitute for the knowledge provided by a detailed site investigation that takes into consideration the extent, nature and location of a proposed development. Therefore the report and maps are primarily intended to give guidance on when to seek specialist advice, and to aid developers in formulating effective investigations. The statutory authorities with responsibilities for different aspects affecting planning and development, should always be consulted at the earliest possible stage of proposals, where their expertise is essential or advisory. A list of these authorities, including those concerned with planning, waste disposal, coal and water, is given in Appendix IV, and reference to them is included in the following text.

All National Grid references in the report lie within the 100 km square SP. Grid references are given to either eight figures (accurate to within 10 m), or six figures for more extensive locations.

Data used in preparing this report and associated maps are lodged at the British Geological Survey, Keyworth. Any enquiries concerning these documents, or about purchase of the report or maps should be directed to the National Geosciences Data Centre, British Geological Survey, Keyworth, Nottingham NG12 5GG.

EXECUTIVE SUMMARY

This study was commissioned by the Department of the Environment to provide an up-to-date database, including new geological maps, as a foundation for the planning of land use and development. The objectives were to complete and produce modern geological maps and accompanying reports; to collect and collate geological and geotechnical data in a form easily understood by non-specialists; and to identify the need for further investigations.

The findings of the study are presented in a report accompanied by a set of Thematic Maps and appendices. The main objective of the report is to provide geological information of direct value to planners and developers. In addition to giving a brief description of the geology of the area, it provides information on the main geological factors affecting planning and development; the nature and extent of mineral resources; the hydrogeology of the area, its water resources, and the aquifer protection policy of the National Rivers Authority; and the engineering characteristics of the various deposits at or near the surface, and the related engineering problems of the deposits.

For the specialist user, a detailed description of the geology of the area, including general features of the formations and members; interpretations of the modes and environments in which the strata were deposited; and the local structure, is given in Appendix I. Attention is also drawn to the most important advances made in understanding the geology of the area. Further appendices describe various aspects of the database.

The Study Area of 375 km^2 (Figure 1) includes the southern extension of the Warwickshire Coalfield, which is defined in general terms by the present workings at Daw Mill and Coventry collieries in the north, by the Meriden Fault in the west, by the outcrop and incrop of the Coal Measures in the east, and by the limits of working imposed by seam depth and thickness in the south. Geographically the study area lies to the east of the West Midlands conurbation within the counties of Warwickshire and West Midlands. It includes the City of Coventry, Kenilworth and parts of Bedworth and Coleshill (Figure 2).

The relief of the area is gently undulating except in the northwest, where it rises more sharply to form the Atherstone-Corley ridge (180 m OD), and to the south and east of Coventry, where it is more subdued and generally below 100 m OD. The main rivers are the Avon, Sowe and Blythe.

The economy of the area is dominated by the industrial base of Coventry. However, this is now undergoing regeneration following the slump in manufacturing industries, especially the car industry, during the mid to late 1970's and early 1980's. Large old industrial sites in the inner city are being replaced by new high technology manufacturing and warehouse-type services on the edges of the city. Surface mineral extraction and coal mining are also important to the local economy. At Little Packington lies one of the largest landfills in Europe, servicing the waste disposal needs of Coventry and the West Midlands conurbation.

In the Coventry area the geological factors affecting planning and development can be categorised as mineral resources, water resources and engineering geology. In the first category, coal and sand and gravel constitute major resources, the extent of which are indicated on the relevant thematic maps. Clay is also extracted for brick making. Two collieries are currently undermining the area and a third is proposed at Hawkhurst Moor. Sand and gravel workings, though not as extensive as in former years, are still important, and the existing resources suggest considerable future potential.

In the category of water resources the Enville Group and the Keele Formation together form an important multi-layered aquifer, yielding large quantities of potable water from boreholes, which it is necessary to protect from agricultural and industrial pollution.

In the category of engineering geology many of the thematic maps need to be considered in assessing the area. A clear understanding of the three-dimensional distribution of the solid rock and superficial drift deposits is vital in the preparation of adequate site investigations, interpreting the results of those investigations, and in predicting the behaviour of these deposits in excavations.

There are seven thematic geology map types in this report dealing respectively with bedrock geology; drift thickness and lithology; sub-drift contours; sand and gravel resources; made ground, surface mineral workings and groundwater resources; and borehole locations. Each theme is presented as a pair of maps at a scale of 1:25 000, and is described in this report. A further section of the report describes the geotechnical properties of the solid rock and drift deposits.

The geology of the area is described in detail in Appendix I. The solid formations range in age from Cambrian to Jurassic, while the superficial deposits are of Quaternary age. Concealed rocks, known mainly from boreholes, include Cambrian and the older Carboniferous strata. Most of the Carboniferous sequence occurs in an open syncline forming part of the Warwickshire Coalfield, with younger beds coming to crop successively southwards. On the west side of the Coalfield the major Meriden Fault throws down Triassic and Jurassic rocks to the west, but these are largely concealed at depth or covered by drift deposits, and they are not well known. Similar Mesozoic rocks also occur to the east of the Coalfield, but again are overlain by an extensive cover of glacial and post-glacial drift.

The main source of data for this study was the field survey by BGS in 1977-80 and 1986-88, supplemented by borehole, geotechnical and other data in the BGS archives. Access to commercial borehole data and mine plans was provided by British Coal; a summary of some of the results of British Coal seismic surveys was provided through a sub-contract, but the seismic sections themselves were withheld by British Coal for commercial reasons. The National Rivers Authority supplied the hydrogeological data. The many other sources of data are listed in Appendix IV.

The results of the survey are available as 1:10 000 scale maps each with an accompanying descriptive open file report. Part of the survey is included in published 1:50 000 scale geological maps 183 (Redditch) and 184 (Warwick), together with their accompanying memoirs (Old and others, in prep; Old and others, 1987).

Although computerisation of the database was not a requirement of the contract funding this study, all the boreholes have been entered on a computerised database through separately funded BGS work. The thematic borehole location maps, and the borehole schedules in the open file reports accompanying the 1:10 000 maps, are examples of the use of this database.

INTRODUCTION

Background

The data provided in this report were obtained largely during a three-year contract, commissioned in 1986 by the Department of the Environment. Funding for the work was shared between the Department and the British Geological Survey.

The study area, comprising 375 km^2, relates to the southern extension of the Warwickshire Coalfield. In general terms the Coalfield is defined by the present workings at Daw Mill and Coventry collieries in the north; the Meriden Fault which marks the limit of economically workable coal reserves in the west; by the outcrop and incrop of the Coal Measures in the east; and by the limits of working imposed by depth in the south. Geographically the study area lies within the counties of Warwickshire and West Midlands, and includes the City of Coventry, Kenilworth and parts of Bedworth and Coleshill (Figure 2).

Aims and Objectives

The study is one of a series commissioned by the Department of the Environment as part of the Geological and Minerals Planning Research Programme (Department of the Environment, 1988a). The work carried out balances the interests of the British Geological Survey, which are primarily in the area of geological research, with those of the Department, which are primarily in the areas of planning and development. It aims to provide an up-to-date geological database, including new geological maps, as a foundation for:

a. land-use planning for development and redevelopment, and

b. effective future geological research.

The objectives are:

a. to complete and produce modern geological maps and reports of those parts of the study area which are not already covered in this way;

b. to collate, collect, evaluate and interpret available information on geological and geotechnical matters for the whole area;

c. to organise the information into a database archive; to present selected basic data and data interpretations as

d. thematic maps and accompanying reports, in a form easily understood by planners and others not trained in geology, mining, civil engineering or related disciplines;

e. to identify the need for further investigations or specialist advice in relation to specific planning and development objectives and proposals.

Work Carried Out Under The Recent Survey

The geological mapping at a scale of 1:10 000 was carried out over most of the southern half of the study area during 1977-80, and of the remainder during 1986-88 together with revision to the earlier mapping. A survey at a scale of 1:10 560 for the northern half of the area, dating from 1913-14, has been incorporated into the new maps where possible, although in many instances extensive revision to the earlier survey was necessary.

The geological field work entailed systematic examination of exposures of solid rock and superficial deposits (drift), together with hand augering to a depth of 1.2m and geological interpretation of topographic features.

The field mapping was augmented by a wealth of borehole and trial pit data, much of which was collected during the survey (Appendix IV). The bulk of this data relates to relatively shallow site investigation or sand and gravel exploration, but a number of coal exploration boreholes and water wells penetrate to considerable depths. Cores from a number of these boreholes were examined, and some have been curated by BGS. An interpretation of the many seismic surveys carried out for coal exploration was provided by British Coal.

Examination of old topographic maps and aerial photographs provided useful information concerning former mineral workings and areas of made ground in the urban area.

Identification of fossils, collected mainly from British Coal boreholes, has assisted in the correlation of the Cambrian and Productive Coal Measures (Table 1; Figure 3).

The component 1:10 000 maps were constructed using a combination of the data sources described above. Each map depicts both lithological and structural variations in the bedrock, and the lithology and distribution of the superficial deposits. A three dimensional interpretation for each map is assisted by means of selected borehole and mining data, and a generalised vertical section. Each map has an accompanying open file report (Appendix V) which gives a general description of the geology together with details of the significant exposures of rock and drift. A complete schedule of boreholes for the map area is appended to each report.

The 1:25 000 scale thematic maps were compiled using data reduced and simplified from the 1:10 000 survey, and from a variety of other sources. Each pair of maps is designed to show one or more geological themes, selected from the database, in summary form for the whole of the study area. Their main purpose is to provide an overview for each theme, and their accuracy is limited by the scale chosen. For more accurate or site-specific data the 1:10 000 geological maps or other parts of the original database should be consulted.

Presentation of Findings

The study is intended to be of value to a wide range of users, from specialists in the earth sciences or related disciplines, to others who may possess only limited specialist knowledge, but who may use the findings as an aid to land-use planning and the formulation of development proposals. The findings are presented in a report accompanied by a set of thematic maps and appendices.

Of greatest value to the non-specialist is the part of the report which gives a description of the geology of the area, and provides information on the main factors affecting planning and development, namely: the nature and extent of the mineral resources; the hydrogeological characterisics of the area, its water resources and the aquifer protection policy of the National Rivers Authority; and the engineering characteristics of the various deposits at or near the surface, and the associated engineering problems.

Seven pairs of thematic geological maps, covering SP27/37 and SP28/38 (excluding 38NE) respectively at a scale of 1:25 000, are provided and described in the report. These are:

- Bedrock Geology (Maps 1 & 2)
- Drift Thickness and Lithology (Maps 3 & 4)
- Sub-Drift Contours (Maps 5 & 6)
- Sand and Gravel Resources (Maps 7 & 8)
- Underground Mining and Coal Resources (Maps 9 & 10)
- Made Ground, Surface Mineral Workings and Groundwater Resources (Maps 11 & 12)
- Borehole Locations (Maps 13 & 14)

For the specialist, a detailed description of the geology of the area is provided in Appendix 1. Also included is information on the general features of the formations and members, interpretations of the modes and environments in which the strata were deposited, and an explanation of the local structure. Attention is drawn to the most important advances made in understanding the geology of the area. Further appendices (II to VI) describe various aspects of the database, including engineering geology.

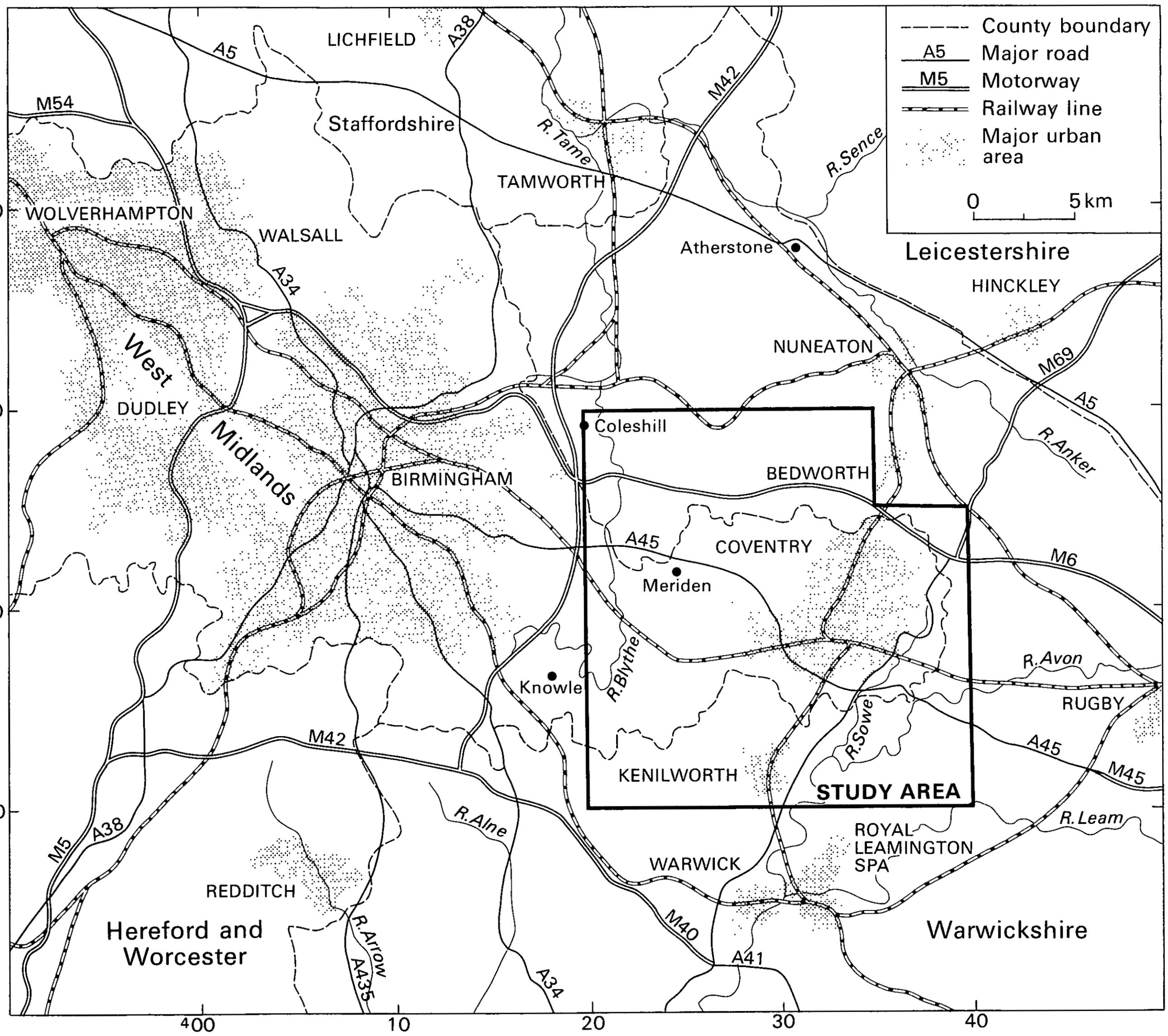


Figure 2. Sketch map showing the regional setting of the study area

GEOGRAPHICAL AND PLANNING BACKGROUND

Physical Setting

The area described in this report is dominated by the densely populated and heavily industrialised area of Coventry. This merges to the north with Bedworth, which is an area of similar character. Lying to the south, the historic town of Kenilworth, famous for its Castle and Abbey, is being increasingly promoted as a tourist centre, but with only a small industrial and commercial base, the town relies on Coventry and Warwick for its employment. The small town of Coleshill lies in the northwest corner of the study area. The urbanised areas contrast sharply with with the surrounding rural areas, which separate Coventry from the adjoining settlements. Of particular importance is the tract of land to the west of Coventry, the so-called "Meriden Gap", which provides an important greenbelt area between the City and the West Midlands conurbation. Much of this land is in agricultural use, but it is interspersed with small pockets of woodland, scattered properties and small villages, the three largest of which are Meriden, Hampton in Arden and Balsall Common. Meriden, with its historic buildings, is identified as "The Heart of England", and as such attracts tourists. Despite being sandwiched between two major centres of population, the area has retained its natural charm and character, making it an important amenity area for people living in the nearby towns and cities.

The M6 motorway and A45 and A46 trunk roads traverse the area, providing valuable links between Coventry and Birmingham and other parts of the country. The area is also crossed by the Birmingham to London (Euston) railway line, while immediately to the west lie the National Exhibition Centre and Birmingham Airport.

Until the mid-1970's the economic prosperity of Coventry and its environs went hand in hand with the success of its manufacturing industries (City of Coventry, 1988). Its car industry, machine tool and engineering firms were all major employers, and led to Coventry being known as a "boom-town" with thriving industries and high wages. In the ensuing decade Coventry, like so many other areas in the country, was hit by an economic recession. Since 1973, more than one in three jobs have disappeared, mostly from the manufacturing sector, with over 40 000 jobs lost in the motor industry alone. For some cities the impact of the rapid loss of jobs in manufacturing, has been replaced by growth in the service sector, including retailing, banking, hotels and catering. This has not happened in Coventry, and as a result the city's economy has been in a weak position. There are, however, the first signs of regeneration; large old industrial sites in the inner city being replaced by new, high technology manufacturing and warehouse-type services on the edges of the city. The catalyst for change has been provided by an available pool of skilled labour, and by Coventry's location at the centre of the Midlands motorway network.

Bedworth, whose small support engineering industries were largely dependent on the car industry, suffered a similar decline to Coventry. It too is undergoing regeneration, but unlike Coventry, it has relied almost exclusively on its excellent communications in attracting the distribution sector of industry.

Outside the built-up areas, mixed pastoral and arable farming predominates. The rural areas, with their historic settlements, are also important for recreational use and tourism.

Mineral extractive industries are also important to the local economy. Coal is currently being mined from two collieries, and a third is proposed to the west of Coventry at Hawkhurst Moor. Clay for brick-making, and sand and gravel provide important sources of raw material for the construction industry. At Little Packington, mid-way between Coventry and Birmingham, lies the largest landfill in Britain which is built up above the original land surface (overland): it services the waste disposal needs of Coventry and the West Midlands conurbation.

The relief of the area is generally undulating, except in the northwest where it rises more sharply to form the Atherstone-Corley ridge (180 m OD), and to the south and east of Coventry where it is more subdued and generally below 100 m OD.

Most of the area lies within the River Avon catchment. The other main rivers are the Sowe, the Sherbourne and the Blythe, while in the northeast, drainage is into the River Anker system.

Planning Context

Planning policies for the West Midlands seek to balance the need for revitalisation of the sub-regional economy and of the inner city areas, against the need to check an unrestricted sprawl of the large built-up areas.

Strategic planning policies for the metropolitan boroughs of Solihull and Coventry are currently contained in the West Midlands County Structure Plan (West Midlands County Council, 1986), and for the outlying areas in the Warwickshire Structure Plan (Warwickshire County Council, 1987). However, following the abolition of the West Midlands County Council, the Secretary of State for the Environment issued Strategic Planning Guidance for the West Midlands, to provide a framework for the preparation of Unitary Development Plans by the metropolitan boroughs, including Solihull and Coventry (Department of the Environment, 1988b). When approved, these plans will replace the West Midlands County Structure Plan. Warwickshire County Council, as a neighbouring authority, is also asked to have regard to the Guidance when reviewing or altering its Structure Plan.

The Strategic Planning Guidance makes provision for 5 000 new dwelling completions in Coventry, and 7 500 completions in Solihull, in the period between April 1988 and March 2001. It also identifies the need for a site for high technology development in Coventry or Warwickshire to meet Coventry's needs and, in addition, for more general industrial development between the eastern periphery of Coventry and the Eastern By-pass. Most of these development requirements will be met from within the confines of the existing urban areas, with only limited incursions being likely into the surrounding areas.

The rural areas are afforded Green Belt status whose function is to prevent neighbouring towns merging into one another; to preserve the special character of historic towns, like Kenilworth; and to assist in urban regeneration. It also protects good quality agricultural land, preserves the quality of the landscape, provides opportunity for sport and helps nature conservation.

Mineral extraction is one form of development which can be appropriate in Green Belt areas, because extraction can only take place where deposits of sufficient quality and quantity occur. In the Report of Issues and Survey Statement to the West Midlands County Structure Plan (West Midlands County Council, 1986), the Blythe Valley, Solihull is defined as being an area where proposals for future sand and gravel extraction may be considered favourably. In the Minerals Plan for Warwickshire (Warwickshire County Council, 1981), areas have also been identified in the Blythe Valley near Packington, and south-east of Coventry, where possible workable deposits of sand and gravel may exist. The Warwickshire and West Midlands County Structure Plans recognise the importance of maintaining an adequate supply of minerals to meet continuing demand, whilst having regard to the need for environmental protection and conservation of good agricultural land.

Environmental protection and need are also cited by both Structure Plans as two of the most crucial issues, by which proposals for a new colliery at Hawkhurst Moor will be judged. They will, however, be matters for the Secretary of State for the Environment to consider, having called in the planning application for determination.

GEOLOGICAL SEQUENCE

The geological sequence of solid rock formations known in the area ranges in age from from Cambrian to Jurassic, while the superficial (drift) deposits are of Quaternary age. The solid rock formations are shown in Table 1 and a generalised vertical section is given in Figure 3. The distribution of outcropping formations is shown in Figure 4.

The study area lies mainly within the central and southern parts of the Warwickshire Coalfield, which is bounded on the western side by the Triassic Knowle Basin (Figure 18). The older rocks, below the upper part of the Etruria Marl, do not come to the surface, and are known mainly from boreholes and colliery workings.

The Warwickshire Coalfield has a synclinal structure, and successively younger Carboniferous and Permian rocks occur towards the south. Triassic rocks, dipping very gently south-eastwards, overlap the eastern side of the Coalfield. In the west a much thicker Triassic and Jurassic sequence is preserved in the downfaulted Knowle Basin, in which most of the Triassic rocks are deeply buried and not fully proved.

The whole area was glaciated in Quaternary times, and there are extensive outcrops of glacial drift (Figure 5), which in places occurs in stratified, mappable units. Post-glacial river terrace deposits and alluvium occur along the main river valleys.

Cambrian

Monks Park Shales and Merevale Shales

The oldest rocks in the area, which have only been proved at depth, are of late-Cambrian age and extend from the top of the Monks Park Shales to the lower part of the Merevale Shales. They consist mainly of dark grey or black marine mudstones with minor proportions of siltstone and sandstone, but the sequence is not known in detail because the rocks have only been proved in short sections in boreholes. Beneath most of the district the Cambrian is buried to depths of 50 to 1200 m and is unlikely to be encountered in site investigation boreholes. Along the eastern margin of the Warwickshire Coalfield, however, Cambrian rocks occur at relatively shallow depth and were penetrated at a depth of 35 m by a site investigation borehole at Clifford Bridge [3761 8079] (Figure 17). Sills of igneous rock (lamprophyre) intrusive into the Cambrian have been encountered in several boreholes, particularly around Fillongley.

Carboniferous (Westphalian A,B,C and D (part))

Productive Coal Measures

A major unconformity separates the Cambrian from the overlying Productive Coal Measures which consist of grey mudstone, siltstone, sandstone and seatearth with a number of coal seams. The only coal seam of economic importance, the Thick Coal, forms the basis of the Warwickshire Coalfield which is entirely concealed beneath younger rocks. In the north-east and around Binley the Thick Coal splits into several individually named seams which have been worked in their own right.

Etruria Marl Formation

The Etruria Marl Formation is also largely concealed beneath younger formations, coming to the surface only near Griff in the extreme north-east of the area. The Formation is a sequence of mudstones, siltstones and sandstones, characterised by variegation in shades of grey, red, brown and yellow. The boundaries of the Formation are rather indefinite, with the base taken at the lowest occurrence of red, brown or yellow coloured beds and the top at the incoming of grey Halesowen Formation beds.

Halesowen Formation

Although the Halesowen Formation comes to the surface along the east side of the Warwickshire Coalfield it is largely covered by drift. Pre-Halesowen folding of the Coal Measures is seen on a number of British Coal seismic profiles, notably near Fillongley and east of Kenilworth, but details of these structures have not been released by British Coal. The Formation consists of grey sandstone and mudstone with a few thin coals and a bed of *Spirorbis* limestone (the Index Limestone).

Carboniferous (Westphalian D (part)) and Permian

The remainder of the Carboniferous and the whole of the Permian consists of red-brown mudstones and sandstones, subdivided into formations dominated by one or the other lithology.

Keele Formation

Mudstone is predominant in the Keele Formation which crops out in the east and north of the area. There are a number of persistent sandstones and several beds of conglomerate and *Spirorbis* limestone.

Enville Group

Sandstone, including several impersistent conglomerate bands, makes up the greater part of the Coventry Sandstone Formation, while in the overlying Tile Hill Mudstone Formation mudstone is predominant, and the sandstones impersistent. The base of the Permian is abitrarily taken at the base of the Kenilworth Sandstone Formation, which consists mainly of sandstone with subordinate mudstone and rare conglomerate. In the overlying Ashow Formation mudstone and sandstone occur in approximately equal proportions.

Triassic

Sherwood Sandstone Group

Another major unconformity occurs at the base of the Triassic Sherwood Sandstone Group. Red, pebbly sandstone and conglomerate of the Kidderminster Formation has been proved in a single borehole, but seismic evidence indicates that the Formation may be present at depth over a wide area to the west of the Meriden (Western Boundary) Fault. Grey and red sandstones make up the bulk of the Bromsgrove Sandstone and there are several impersistent beds of red-brown mudstone.

Table 1. Succession of solid geological formations

Jurassic	Lias Group		Saltford Shale Member: Grey shale with limestone bands	15m
Triassic	Penarth Group	Lilstock Formation	Langport Member: Porcellanous grey limestone	0.2–2.0m
			Cotham Member: Grey-green calcareous mudstone	8m
		Westbury Formation	Dark grey mudstone	8m
	Mercia Mudstone Group	Blue Anchor Formation	Grey-green siltstone and mudstone	7m
		Undivided	Red-brown mudstone with thin grey-green siltstone and sandstone bands and Arden Sandstone	180–450+m
	Sherwood Sandstone Group	Bromsgrove Sandstone Formation	Brown micaceous sandstone and red-brown mudstone	25–180m
		Kidderminster Formation	Red-brown pebbly sandstone and conglomerate	0–578+m
Permian	Enville Group	Ashow Formation	Red-brown mudstone and sandstone	175m
	Autunian to Westphalian D	Kenilworth Sandstone	Red-brown sandstone and mudstone with thin conglomerates and breccias	100m
Carboniferous		Tile Hill Mudstone	Red-brown mudstone with sandstone and siltstone	250–300m
		Coventry Sandstone	Red-brown sandstone and mudstone with Corley Member: pebbly sandstone and conglomerate	300–550m
	Westphalian D	Keele Formation	Red-brown mudstone and sandstone	155–370m
		Halesowen Formation	Grey sandstone and mudstone with thin coals	50–150m
	Westphalian C	Etruria Marl Formation	Variegated mudstone and coarse sandstone	30–150m
		Productive Coal Measures	Grey mudstone, siltstone, sandstone and seatearth with coal seams Aegiranum Marine Band Vanderbeckei Marine Band	75–180m
	Westphalian B			
	Westphalian A			
Cambrian	Tremadoc Merioneth	Merevale Shales Monks Park Shales	Grey mudstone Dark grey mudstone	Unknown

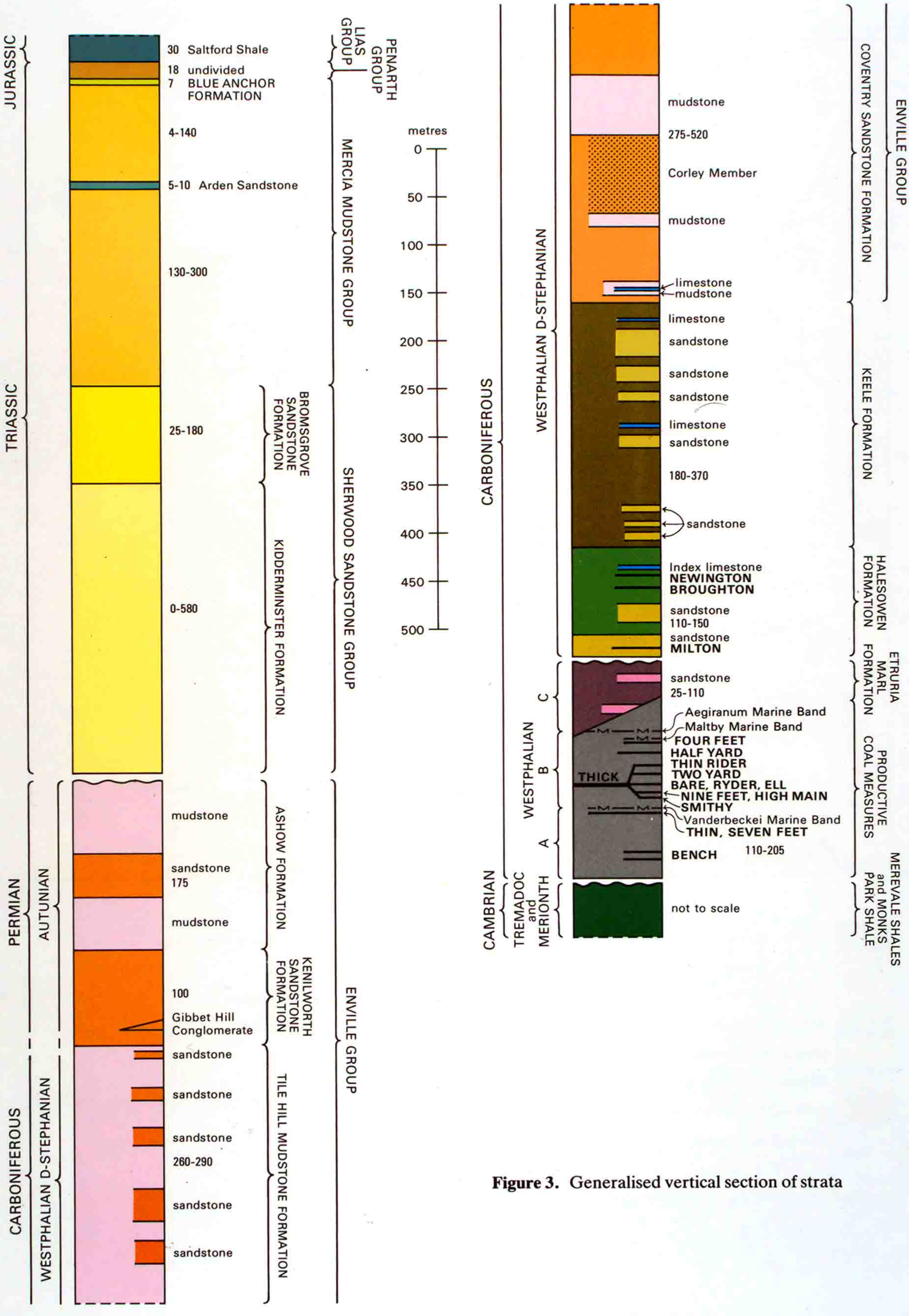


Figure 3. Generalised vertical section of strata

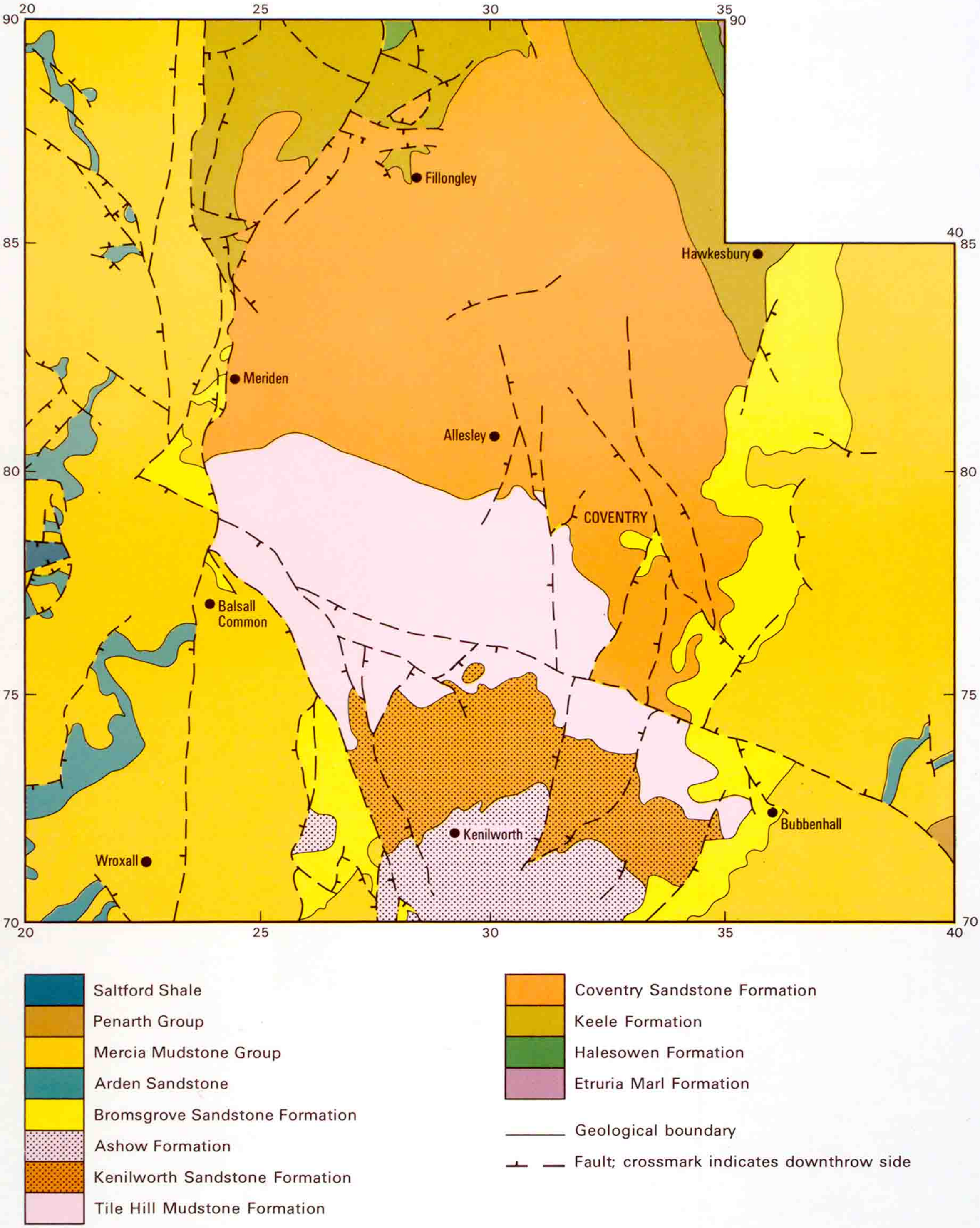


Figure 4. Simplified geological map of the study area

Mercia Mudstone Group

Much of the outcrop of the Mercia Mudstone Group (formerly known as "Keuper Marl") is covered by drift and the sequence is imperfectly known. While red-brown mudstone predominates there are several persistent sandstone or siltstone horizons, the most important of which is the Arden Sandstone.

The Blue Anchor Formation at the top of the Mercia Mudstone, and the overlying Penarth Group have a small subcrop beneath the faulted inlier of Saltford Shale Member at Barston, and a small outcrop in the south-east.

Jurassic

The Triassic/Jurassic boundary occurs within the Saltford Shale, which consists of thinly bedded calcareous mudstones and limestones.

Quaternary

Deposits of glacial and post-glacial drift (Table 2) occupy considerable outcrops (Figure 5), and large drift-covered areas were discovered west and north-west of Coventry where previous geological maps showed little or no drift.

All the glacial drift appears to be the product of a single glacial stage, which is of uncertain status (Appendix 1), but is known as the Wolstonian. In the east and south-east it occurs in a recognisable stratigraphic sequence (Table 1) which can be correlated with the type Wolston Series just to the east. Elsewhere there is no consistent drift stratigraphy and the inter-relationship of the drift lithologies may be complex. The glacial deposits consist of sand and gravel, boulder clay (till) and laminated stoneless clay and silt.

The post-glacial deposits consist mainly of flights of river terraces, composed of sand and gravel, and alluvium.

Table 2 Stratigraphy of the drift deposits

Stage name & age where known	Drift stratigraphy	
FLANDRIAN 10,000 B.P. to present day	Alluvium Avon and Blythe First Terrace	
DEVENSIAN 50,000 to 10,000 B.P.	Avon and Blythe Second Terrace	
IPSWICHIAN	Avon Third Terrace Avon Fourth Terrace	
WOLSTONIAN	Western Glacial Drift	Eastern and Northern Glacial Drift
	Fluvio-glacial Sand and Gravel Boulder Clay Sand and Gravel Glacial Lake Deposits	Dunsmore Gravel Chalky and Flinty Boulder Clay (Oadby Till) Sand and Gravel (Wolston Sand and Gravel) Glacial Lake Deposits (Wolston Clay) Triassic-derived Boulder Clay (Thrussington Till) Baginton Sand and Gravel

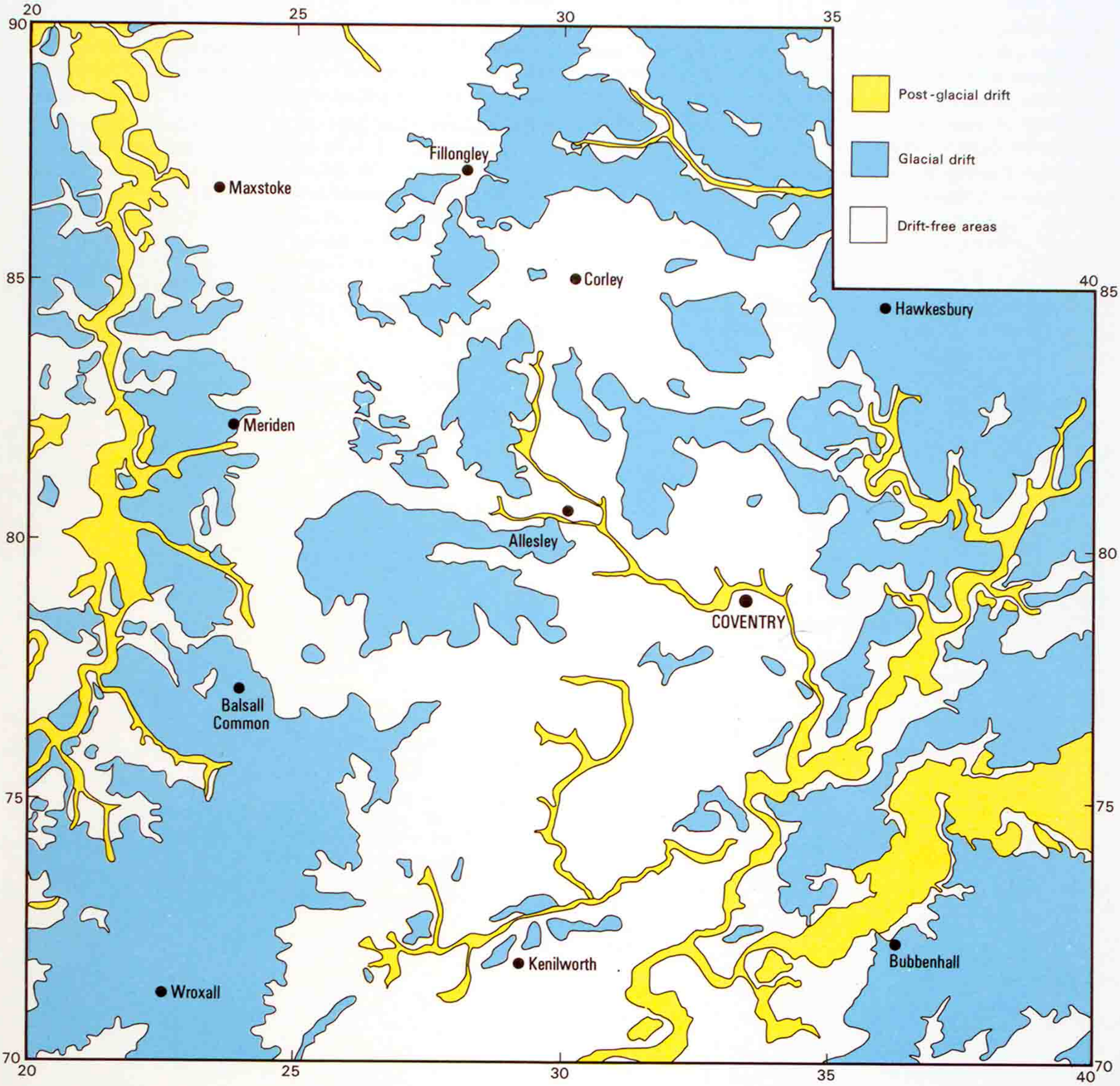


Figure 5. Distribution of drift deposits

GEOLOGICAL IMPLICATIONS FOR PLANNING AND DEVELOPMENT

This section of the report sets out the main categories in which geological conditions may have an influence on land-use planning and development. Further information relating to these categories is given in the descriptions of the thematic maps. Three main categories have been identified, all of which ought to be considered in the making of planning decisions, namely:

Mineral resources
Water resources
Engineering geology

It is emphasised that only general statements are made in this report, in some cases based on limited data, and further investigations are always likely to be necessary to clarify specific problems.

Mineral Resources

Under this category are included brick clay, coal and sand and gravel.

Brick Clay

Although a number of formations have been, or are, currently worked for brick clay, economic considerations largely mitigate against the establishment of new brick making plants. Resources of brick clay are very extensive in the study area; the life of permitted reserves at Jackson's Brickworks [207 825] is likely to be considerable, whereas reserves at the Midland Brickworks [342 805] are much more limited.

Coal

Coal has or could be mined beneath most of the area east of the Meriden (Western Boundary) Fault of the Warwickshire Coalfield (Maps 9 and 10). Planners and developers should always contact British Coal in the first instance regarding all aspects of underground mining. The area to the west of the Meriden Fault has not been prospected for coal, and there is a possibility that further resources underlie that area. The effects of mining-induced subsidence in this area are described in the section on Engineering Geology.

Sand and Gravel

Sand and gravel resources are shown on Maps 7 and 8 and the working pits are listed in the corresponding text. They occur in the glacial and post-glacial deposits. Planners and minerals operators need to know the location and extent of sand and gravel deposits of economic quality, so that decisions can be taken on safeguarding them from other development, and on their potential for extraction.

Sand and gravel is worked in open pits which may be up to 15m deep in this area and may occupy extensive areas within productive agricultural land. Abandoned workings generally become flooded when unrestored, and where workings, particularly older ones, have been restored, their former extent is not always well known.

Water Resources

The main aquifers in the study area are the Keele Formation and the Enville Group, both of which have extensive outcrops. The Bromsgrove Sandstone is a minor aquifer. Although the Quaternary sand and gravel deposits are not important aquifers in terms of water supply, they are probably in hydrogeological continuity with the solid rock aquifers and so themselves need to be protected from pollution.

Aquifer Protection Policy

It is a responsibility of the National Rivers Authority to ensure that existing and potential groundwater resources in its area are adequately protected. The prevention of quality deterioration is therefore an essential aspect of water resource management. Groundwater currently provides some 40% of the total public water supply in the Severn Trent Region, and it features prominently in future resource strategy. The Authority has therefore introduced an aquifer protection policy which is implemented within the framework of the present legislative controls. Those most relevant to groundwater pollution are:-

Control of Pollution Act 1974, Parts I and II.
EEC Directive on the Protection of Groundwater Against Pollution caused by Certain Dangerous Substances (80/68/EEC).
Town and Country Planning Act 1971.

The policy recognises different categories (called zones) of land which require different degrees of protection, depending on the proximity to a public supply borehole and the hydrogeological parameters of the rocks. The policy document is comprehensive and full details are available from the Authority. The Permo-Carboniferous outcrop of the Coventry area falls within Zones 1 and 2 of the policy. Zone 1 is that area within a 1km radius of existing or designated future groundwater sources for public supply (Maps 11 and 12). Within Zone 1 the Authority will usually object in principle to all development proposals which would result in pollution of a groundwater source. Zone 2 comprises the major aquifers, such as the Permo-Carboniferous, but excluding Zone 1. The areas comprising Zone 2 will also receive a high degree of protection, to ensure that neither current nor future abstraction is needlessly restricted. However, the controls are not as stringent as those for Zone 1. Activities to which an objection would normally be made include:

a) Waste disposal sites intended to receive substances hazardous to water supplies.

b) Major industrial developments which involve the use, production, storage, or handling of toxic materials, unless adequate protective measures are agreed.

c) The disposal of sewage effluents by aquifer recharge.

Groundwater Management Units

In order to assist in the determination of new groundwater licenses the Permo-Carboniferous is divided by area into three management units: Coventry, Meriden, and Kenilworth (Maps 11 and 12). The current resource balance for these units is:-

Groundwater Unit	Assessed Resources (Ml/d)	Licensed Abstractions (Ml/d)	Actual Abstractions (1988) (Ml/d)
COVENTRY	16.6	26.8	18.4
MERIDEN	28.7	13.2	12.1
KENILWORTH	22.4	6.8	5.2

The Meriden and Kenilworth units are under-licensed and new licences are usually granted. For the Coventry unit, whilst actual abstractions approximate to the resource, there is an imbalance between licensed abstractions and the resource. This is because under the Water Resources Act (1963) any groundwater abstractions in existence at that date were automatically granted a licence (Licence of Right). The present policy for the Coventry unit is to look critically at new licence applications as well as encouraging industry to reduce the large unused component of their current licences.

Observation Borehole Network

As required under Section 18 of the Water Resources Act 1963 the National Rivers Authority monitors long term changes in water levels in the major aquifers. In the general area of Coventry the following boreholes, within the Permo- Carboniferous, are used for monitoring purposes:-

Name of Borehole	N.G.R.
Peugeot Cars	SP 351 782
Stoney Road	SP 333 781
Rolls Royce	SP 335 782
Coventry Dairy	SP 348 801
Jaguar (Radford)	SP 332 808
Courtaulds (Little Heath)	SP 348 826
New House Farm	SP 331 856
Church Lane	SP 297 850
Ivy Farm	SP 308 767
Broad Lane	SP 306 787
Kingswood	SP 316 734

This information is used to assist in:

a) The determination of any major rises or falls in groundwater levels. The resultant trends are then used as an aid to evaluate whether any new groundwater licences should be granted.

b) Formulating statutory replies to Waste Disposal Authorities regarding landfill site planning applications; the depth to water table being an important factor in assessing whether a site is suitable for waste disposal.

c) Replying to enquiries received from planners, engineers and others who may want specific information relating to groundwater levels.

Engineering Geology

The report presents a synthesis of the available geotechnical data relevent to planning and development, with an emphasis on the foundation properties of bedrock and superficial (drift) deposits. Full geotechnical data for the study area are given in Appendix II, and descriptions of the geotechnical tests quoted in the report are given in Appendix III.

The interpretation of the geotechnical database provides an overview for each geological formation for which sufficient data exist, and is not intended to be used as a substitute for site investigation. Also it is possible that anomalous ground conditions exist undetected at any particular site. Each site should, therefore, be investigated by a detailed survey, with the drilling of exploratory boreholes to prove the ground conditions present, after taking into account the nature, extent and setting of the proposed development.

THE THEMATIC GEOLOGICAL MAPS

The results of this survey are presented as a series of thematic geological maps at a scale of 1:25 000. Each theme occurs on two sheets numbered as follows:

Theme	SP 27/37 Map No.	SP 28/38 Map No.
Bedrock Geology	1	2
Drift thickness and lithology	3	4
Sub-drift contours	5	6
Sand and gravel resources	7	8
Underground mining and coal resources	9	10
Made ground, surface mineral workings and groundwater resources	11	12
Borehole locations	13	14

Bedrock Geology (Maps 1 and 2)

These maps depict the bedrock (solid) geological formations at outcrop. The outcrops of superficial drift deposits are also shown but are not subdivided according to lithology on these maps (see Maps 3 and 4). Lithological descriptions of the formations are given in Appendix I and in the open file reports accompanying the 1:10 000 maps, and additional structural information is shown on Maps 9 and 10 and on the 1:10 000 maps.

Drift Thickness and Lithology (Maps 3 and 4)

These maps show the lithological subdivision of the drift deposits but no details of the solid geology (see Maps 1 and 2). Detailed descriptions of the drift deposits are given in Appendix I and in the open file reports accompanying the 1:10 000 maps. Drift deposits less than 1m in thickness have not generally been mapped. Many of the drift deposits are characterised by rapid lateral and vertical variations, which can lead to difficulties in accurately predicting site conditions.

The drift thickness contours show the total drift thickness in metres, and are based mainly on borehole data, and drift sequences exposed in excavations and mineral workings. Therefore, considerable uncertainty exists where borehole data are sparse. The thickness of individual lithologies in multilayered sequences is not shown, but is commonly indicated on the 1:10 000 maps. Sand and gravel thicknesses are shown on Maps 7 and 8.

Sub-Drift Contours (Maps 5 and 6)

These maps depict the topography of the sub-drift (rockhead) surface, which is primarily that beneath glacial drift. By comparison with Maps 3 and 4 it can be seen that the thickest accumulations of drift in the east lie upon a relatively subdued topography whereas in the west there are several drift-filled valleys. As with the drift thickness contours the accuracy of these maps is directly related to the density of boreholes proving the base of the drift.

Sand and Gravel Resources (Maps 7 and 8)

These maps show outcrops of glacial and post-glacial sand and gravel which lie outside the urban areas. Areas of sand and gravel beneath overburden are also shown where the overburden to sand and gravel ratio does not exceed 3:1. Abandoned and active workings are indicated and a list of the latter is given below.

Site	NGR	Operator
Berkswell	225 805	RMC–Western Aggregates
Brandon Wood	383 763	Steetley Construction Materials
Meriden (Cornets End)	234 813	Tilcon
Waverley Wood	364 714	Smiths Concrete

The data for sand and gravel beneath overburden is modified from BGS Mineral Assessment Reports by Cannell (1982), Crofts (1982), and Cannell and Crofts (1984), and these reports contain numerous grading analyses of sand and gravel from boreholes drilled specially to assess these deposits (see also Figures 11c and 12). A further report (Clarke and others, 1982) describes various experimental techniques used for sand and gravel assessment, and the subsequent application of resistivity soundings is recorded by Cannell and Crofts (1984). The only area not covered by the above reports, and where significant sand and gravel resources occur, is the section of the Blythe Valley east of Coleshill on sheet SP28NW.

Much of the sand and gravel to the east of Coventry, where the major resource was the Baginton Sand and Gravel (Plate 1), has either been extracted or sterilised. The most important resources now lie in the west, particularly in the Blythe Valley and north-west of Balsall Common (Plate 2), and include extensive outcrops of river terrace deposits east of Coleshill, newly discovered during the present study.

Underground Mining and Coal Resources (Maps 9 and 10)

These maps indicate where underground coal mining has taken place and where it may occur in the future. Very small areas around Hawkesbury have been undermined by workings for ironstone but these coincide with areas of coal mining and have not been shown separately. *Spirorbis* limestone was worked from shallow shafts west of Bedworth, but the extent of the workings is unknown, although it is likely to have been small.

The shallow pre-20th Century abandoned workings along the eastern margin of the coalfield are not as well documented as those abandoned more recently. It is possible that small areas of undermined ground exist which are not shown on the maps, and that there are unrecorded mine shafts in the same area. A history of the Warwickshire Coalfield up to 1913 is given by Grant (1982), and further details are given by Mitchell (1942), National Coal Board (1957) and Old and others (1987).

Within the area not yet undermined the only seam of economic importance is the Thick Coal, and the seam data shown on the maps have been supplied by British Coal. Currently the Thick Coal is worked from Daw Mill and and Coventry collieries and a new colliery has been proposed for Hawkhurst Moor (National Coal Board, 1985; British Coal, 1987). At present there are no proposals to work coal at depths greater than 1200 m below surface.

Brick Clay Resources (Maps 1,2,11 and 12)

Brick clay is currently worked at Jackson's Brickworks, Solihull [207 825] where the raw material is Mercia Mudstone (Plate 3), and at Websters, Hemming and Sons Ltd., Midland Brickworks, Coventry [342 805] sited on mudstones and sandstones of the Coventry Sandstone (Plate 4). Jackson's Brickworks produces facing bricks, and the Midlands Brickworks facing and semi-engineering bricks. There were formerly brickworks in the Ashow Formation at Kenilworth [294 721, 294 717] and in the Keele Formation at Longford [350 842; 349 856]. Shallow former brick clay pits in Coventry Sandstone west of Barkers' Butts Lane [322 800] are too small to show at this scale, but are shown on 1:10 000 sheets SP37NW and SP38SW.

All the outcropping Carboniferous formations together with the Mercia Mudstone Group are potential sources of brick clay, and future exploitation is likely to depend much more on economic and environmental, rather than geological considerations.

Made Ground, Surface Mineral Workings and Groundwater Resources (Maps 11 and 12)

Made Ground

Made ground as shown on the maps is confined to material built up above the previous natural land surface and which generally has a clear topographic expression. Road and railway embankments have not been shown except where they are contiguous with other areas of made ground. The older urban centres, notably Coventry within the area enclosed by the Inner Ring Road, have been affected by successive periods of development and rebuilding which have produced a layer of made and disturbed ground several metres thick. Only the clearly defined parts of this made ground are shown on the maps.

Most areas of made ground are likely to consist of a heterogeneous mixture of building rubble, excavated rock and soil, and domestic and industrial refuse. No attempt has been made, therefore, to categorise the made ground according to its composition, except in the case of colliery spoil mounds which have a clearly identifiable source.

Surface Mineral Workings

The surface (opencast) mineral workings in this area are mainly in sand and gravel deposits, with a few in brick clay. Borrow pits were opened at Walsgrave Hill [391 805] and Binley Woods [390 772] to provide constructional fill for the Coventry Eastern Bypass. The pits were backfilled with material excavated from the Bypass route, but which was unsuitable for use in the road works. All but the most recently worked areas are now wholly or partially restored with a variety of fill materials, including all those also found in made ground.

Where recent landfilling of opencast workings and creation of made ground has involved putrescible material, there is a possibility that potentially hazardous landfill gas will be generated. A comprehensive account of current knowledge and utilisation of landfill gas is given in Alston and Richards (1988), while a Waste Management Paper (Her Majesty's Inspectorate of Pollution, 1989) provides information on the formation of landfill gas, and the current state-of-the-art with regard to its monitoring and control.

The Little Packington landfill site, to the south of Coleshill [205 853], was started in a void created by sand and gravel extraction. With subsequent extensions it now covers 156 ha, and with recent planning permission to raise the original ground level by 60 m to reach a height of 150 m OD, it has become the largest overland landfill in the United Kingdom, and one of the largest waste disposal sites in Europe. It is claimed to accommodate 15% of all the domestic, commercial, industrial and construction industry wastes arising from the West Midlands. The landfill operation is carefully controlled through the use of clay-lined cells, which serve to minimise leachate generation. The operator has also installed one of the largest and most innovative landfill gas recovery and control systems in the UK, the gas being used to generate electricity for the national grid (Packington Estate Enterprises Ltd., 1987; Biddle, 1988).

Groundwater Resources

The sites of the most important water boreholes licensed by the National Rivers Authority are shown on the maps with their BGS registered numbers. Abstraction data are shown in Table 3: actual abstraction rates for private boreholes are confidential. Geological details of the boreholes are given in the open file reports accompanying the 1:10 000 maps.

Further information on wells past and present, including water analyses, is included in Anon (1950), Butler (1946), Eastwood and others (1923), Lyon (1949) and Richardson (1928).

Borehole Sites (Maps 13 and 14)

These maps show the sites, boreholes and trial pits registered in the BGS database. Complete borehole schedules for each 1:10 000 sheet including the BGS registration numbers are appended to the appropriate open file report.

The original non-confidential records may be examined at the BGS National Geosciences Data Centre, Keyworth, Nottingham, NG12 5GG, by prior appointment, or copies of records can be sent in response to postal enquiries, in either case on payment of the current fee. Confidential records may be examined only after permission has been granted by the owner of the information.

Individual records vary from simple lithological logs to complete site investigation reports and detailed lithological descriptions. The computerised database allows cross-referencing to other BGS data including specimens and geophysical borehole logs. (For further information see Appendix IV).

Plate 1 Cross-bedded glacial sand and gravel becoming increasingly sandy upwards. Baginton Sand and Gravel, Waverley Wood Quarry [3681 7120]. A14561.

Plate 2 Cross-bedded glacial sand with minor quantities of gravel; overlain (top centre) by darker brown fluvio-glacial sand and gravel. Depth of pit 15m. Cornet's End Quarry [2357 8155]. A14552.

Plate 3 Thin bedded mudstones in Mercia Mudstone Group. 15m face, Jackson's Brickworks [205 826]. A13524.

Plate 4 Thin bedded mudstones and sandstones in Coventry Sandstone Formation. Websters, Hemming and Sons Ltd., Midland Brickworks [3423 8050]. MN27148.

Table 3. Water abstraction data for major licenced wells in 1984. (Source: Severn Trent Water Authority, 1986). BS=Bromsgrove Sandstone, CS=Coventry Sandstone, KF=Keele Formation, KS=Kenilworth Sandstone, TH=Tile Hill Mudstone, Ml/d= megalitres per day (1 Ml/d=9164 gallons per hour).

BGS No	Name	NGR	Licenced Abstraction (Ml/d)	Actual Abstraction (Ml/d)	Depth (m)	Aquifer
SP27NE/46	Mount Nod	2922 7927	3.04	2.75	216	CS
SP27SE/13	Mill End	295 728	3.47	2.14	81	KS,TH
/14	Birmingham Rd	2830 7323	0.45	0.41	174	KS,TH
SP28NE/10	Daw Mill	2651 8992	0.24		150	
SP28SE/6,7	Meriden	2624 8262	6.83	6.37	203	
	Arnold	250 827	0.15			
SP37NW/2,						
263	Spon End	322 791	4.52	4.49	130	CS
136	Green Lane	3220 7598	2.17	2.00	160	TH,CS
232	Rolls Royce	3359 7828	0.02		54	CS
265	Unipart	3060 7811	2.09		259	CS
280	Stoney Road	3337 7814	1.56		71	CS
302	Rolls Royce	3381 7808	1.24		85	CS
	Montgomery Plating	340 790	0.20		84	CS
	GEC/AEI	328 789	0.25			CS
SP37NE/22	Whitley	3577 7673	3.04	0.008	76	BS,CS
25	Talbot Motors	3513 7825	0.50		158	CS,KF
28	GEC No 4	3621 7876			136	BS,CS,K
29	GEC No 3	3620 7837	1.59		122	BS,CS,K
30	GEC No 2	3620 7845			115	BS,CS,K
SP38NW/124	Newdigate (with Bedworth)	3350 8685	2.02	1.50	67	
SP38SW/5	Watery Lane	324 835	2.17	2.13	236	CS
101	Dunlop Ltd	3304 8213	1.45		166	CS
109	Brownshill Green	3063 8270	3.04	1.64	91	CS
120	Dunlop Ltd	3821 8218	0.83			CS
122	Brit. Celanese	3488 8261	3.45	(including	159	CS,KF
123	Brit. Celanese	3476 8259		SP38SE)	149	CS,KS
	Brit. Coal, Coventry	321 844	1.89	3.713	74	CS
130	Jaguar Cars	3327 8085	1.11		188	CS
133	Courtaulds No 2	3380 8076			214	CS
134	Courtaulds No 3	3365 8083	5.35		294	CS,KF
137	Courtaulds No 8	3408 8079			243	CF,KF
138	Courtaulds No 7	3424 8032			244	CS,KF
141	Coventry Co-op	3492 8022	0.07		221	CF,KS
SP38SE/4	Brit. Celanese	3525 8270		(including	198	CS,KF
171	Brit. Celanese	3554 8235	3.45	SP38SW)	150	CS,KF

THEMATIC (APPLIED) GEOLOGY MAPS AND THEIR USERS

The DoE, in its programme of commissioned geological research, has taken the view that thematic (applied) geological maps are, if properly designed, a more easily understood and more comprehensive way of presenting information to those involved in land-use planning and development, some of whom have little geological or geotechnical training.

The maps are aimed principally at *planners* who should find them of value for formulating planning policies for development and redevelopment, and *developers* concerned to identify areas where suitable sites might be found. Planners will be concerned, for example, to identify areas of sand and gravel resources and avoid their unnecessary sterilisation by development; similarly they will want to know the location of aquifers in order to safeguard them from unnecessary development, or pollution by unsuitable waste disposal policies. They will also need to have available background geotechnical data in order to assess properly, proposals for surface development and to identify geological constraints to development. Developers and their consultants need firstly: general background geotechnical and mineral resource information to undertake feasibility studies of possible sites for civil engineering and building works; and secondly, guidance concerning the availability of site investigation reports in or near their areas of interest.

ENGINEERING GEOLOGY

This section of the report assesses the geotechnical database collected as part of the project; describes the geotechnical properties of the principal formations in the study area; and assesses the engineering geology of these formations, in general terms, based largely on lithological and geotechnical characteristics. Full geotechnical data for the study area are given in Appendix II, and descriptions of those geotechnical tests quoted in this section are given in Appendix III.

The Geotechnical Database

The geotechnical samples reported on here were obtained mainly by shell and auger or rotary drilling, with a smaller number derived from trial pits. More data were available for cohesive than non-cohesive materials. There was a wide variety in the quality of data and, in general, poor quality data were ignored. Consequently, the quantity of data included in the database is less than might be expected for such a large area. This has been compounded by the frequent non-availability of geotechnical data on the grounds of confidentiality. Careful validation of the stratigraphical data showed that those formations having the largest number of data records were the Coventry Sandstone, boulder clay and Mercia Mudstone (undivided), followed by the Keele Formation, Wolston Clay and alluvium. Small numbers of records were found for glacial sand and gravel, Bromsgrove Sandstone, Ashow Formation, Kenilworth Sandstone, Baginton Sand and Gravel, Tile Hill Mudstone and Arden Sandstone.

Data were extracted from site investigation reports (the majority being for road construction projects), reduced to S.I. units or coded scales where necessary, and entered into an IBM PC(XT) computer database. Statistical interpretation and graphical presentation were carried out using a commercial software package.

The database consists of 35 variables and 2,312 records. With the exception of the Mercia Mudstone, very little geotechnical work, either of a research or a commercial nature, has been reported in the literature for the formations found in the study area.

Broadly speaking, the bedrock lithologies are dominated by red-brown sandstones and mudstones (or clay), with most Carboniferous, Permian and Triassic formations consisting of interbedded sequences of these two lithologies. Formations older than Westphalian D and all Jurassic formations, together with coal and ironstone, are absent from the database. The geotechnical database representing superficial deposits consists of data from boulder clay (mainly Thrussington Till), laminated glacial lake deposits (Wolston Clay), glacial sand and gravel (including the named Wolston and Baginton units) and alluvium (undivided). Head (colluvium) is not represented in the database. Made ground (undifferentiated) is represented but is not described in this section.

An 'engineering lithology' code, which summarizes the essential lithological description by letters (e.g. c = clay, s = sand, etc) has been added to each record in the database.

Geological Problems in Engineering Practice

Because many of the geological problems relating to engineering encountered in the study area cross stratigraphic boundaries, the stratigraphic units are not described separately (Table 6). The ubiquitous bedrock sequences of sandstones, clays and mudstones of the Carboniferous, Permian and Triassic possess, with few exceptions, a similar suite of geotechnical characteristics, as far as these are recorded. The overlying drift, 80% of which is glacial in origin, covers approximately 50% of the surface of the study area. Problems which have been identified directly from site investigation reports, and recorded case histories, are summarized below.

Weathering

Throughout the literature (Chandler, 1969; Cripps and Taylor, 1981; Davies, 1971; Eyles and Sladen, 1981), the importance of weathering on the properties of both bedrock and glacial drift has been highlighted. Standardized weathering zones to describe bedrock have been introduced (Chandler, 1969) but many site investigations, including modern ones, ignore their use. The correlation between weathering grade and geotechnical properties, and hence engineering behaviour, has been clearly demonstrated. Important mechanical and chemical changes occur from one weathering zone to another, and these should be recognized, preferably in the form of a weathering zone profile with depth. In the case of mudrocks and clays, many of the properties associated with over-consolidation are modified by weathering; effective strength is reduced, while plasticity and deformability are increased. In the case of sandstones, weathering breaks down cementation particularly where this is weak, resulting in loss of strength. This process is accelerated by the presence of numerous discontinuities through which the weathering process attacks the fabric of the rock. Confusion has been encountered in many of the site investigations between weathered bedrock and boulder clay (possibly due, in part, to poor sampling techniques), and many lithostratigraphic descriptions from these reports have been amended in the database.

Rockmass structure

Site investigators often pay little attention to discontinuities and other structural features within both bedrock and drift. For example, the nature and infill, if any, of joints and faults within massive sandstones, are important considerations for large-scale engineering works. These features often affect mass properties, such as permeability and strength, to a greater extent than the intact fabric of the rock. Joints and faults, particularly in blocky sandstones, have an important influence on the nature of mining-induced subsidence. Unexpected features of glacial origin may also affect the mass engineering behaviour of drift. The unpredictable nature of the drift/bedrock boundary, particularly its depth below ground level, may influence settlement, bearing capacity, slope stability and the local groundwater regime. Drift tends to conceal important structural features, such as faults within the underlying bedrock.

Subsidence

The greatest potential subsidence hazard lies in the narrow belt of shallow, ancient workings along the eastern outcrop and sub-crop of the Coalfield, where it is possible that there are unrecorded workings and shafts. The extent of more recent, deeper workings or of proposed workings is well known. Instances are recorded, in the east and north-east of the study area, of flooded and low-lying boggy ground attributable to subsidence above old, shallow, pillar-and-stall colliery workings. In these areas high water tables and infiltration have led to softening and weakening of weathered bedrock. Subsidence has also resulted in disturbances to bedrock, such as the opening of joints due to tensional stresses, and possibly the formation of voids. As a result, deep piling operations in these areas have in one reported instance experienced problems, and alternatives may need to be considered. Subsidence due to modern total-extraction methods is generally more rapid and more predictable than that due to pillar-and-stall methods (Waltham 1989). However, a predominance of massive sandstone beds, such as those in the Sherwood Sandstone Group, can cause more severe and more erratic subsidence. Joints or fractures may be opened by tensional forces or closed and uplifted by compressional forces.

Sulphates

High sulphate contents, due to the presence of gypsum, may occur particularly within the Mercia Mudstone. They pose the threat of chemical deterioration of normal concrete, and require the use of sulphate-resisting cement and possibly protective coatings in foundations. Sulphates may also be leached by groundwater into immediately overlying drift.

Pollutants

Industrial chemicals can present problems in bedrock, drift and, particularly, aquifers, when leached by groundwater from polluted fill, such as may be found underlying old industrial sites.

Settlement

Differential settlement is a common problem in areas of glacial drift, where unexpected lithological and thickness changes take place over short distances. Structures founded partly on bedrock and partly on drift are particularly prone to such settlement. A pre-glacial bedrock profile is often irregular and may be cut by channels infilled with drift; in such cases the glacial drift itself is commonly highly variable lithologically and geotechnically. The compressibility of the bedrock may be of importance; for example, weak sandstones may exhibit significant creep deformations under sustained high loads. This effect is increased by the presence of clay bands and/or mining subsidence.

Groundwater

Water-bearing bands or lenses of glacial sand and gravel are sometimes bounded by 'impermeable' boulder clay. In some instances, these aquifers may be confined or perched, i.e. independent of and above the main water table, which may be at depth within bedrock. Their presence, which can be inferred from reduced SPT blow counts, results in instability of excavation walls and seepage of water into excavations and boreholes, sometimes causing "running-sand" conditions. Prolonged seepage may result in softening of any adjacent clay.

Slope stability

Natural landslips are believed to be small and few in the study area. A suspected shallow landslip in Wolston Clay, identified at Walsgrave Hill close to the route of the Coventry Eastern Bypass [391 806] , was subsequently removed. In general, however, topographical and hydrogeological conditions in the study area do not favour natural landslip formation. The design of cut slopes is very dependent on local geological and hydrogeological conditions, and the scale of the engineering works. Slopes of 1V:1H (45°) have been recommended for boulder clay where groundwater can be controlled. No information is available for other lithologies, although the Wolston Clay, with its high plasticity, may require special precautions. Reliable estimation of the stability of cut slopes in overconsolidated clays and interbedded sequences is difficult, and slopes in these materials tend to deteriorate with time. Stress relief and water infiltration result in softening and loss of strength, while swelling and heave at the base of excavations in overconsolidated clays may occur, particularly where a non-saturated clay is exposed to the elements or subjected to infiltration of groundwater.

Analysis and Synthesis of the Geotechnical Database

The geotechnical data collected can be subdivided into the following categories, each of which is explained fully in Appendix III:-

a) Index test data – Liquid limit, plastic limit, moisture content, density, particle size – carried out to British Standards (Anon, 1975). From these, plasticity index and liquidity index were calculated.
Few particle size analyses were found for the cohesive deposits.

b) Chemical test data – Sulphate content (total in soil), pH.

c) Strength test data – Triaxial (largely unconsolidated, undrained type), SPT and RPT field tests, and a small number of shear box tests on 'undisturbed' specimens.

d) Compressibility (Consolidation) test data.

e) Compaction and CBR (California bearing ratio) test data carried out to British Standards (Anon, 1975).

f) Rock mass assessment data – RQD (rock quality designation) and fracture spacing.

A statistical summary of geotechnical data is given in Table 4; modified 'box and whisker' diagrams for selected non-parametric data are given in Table 5. These diagrams show percentiles in the form of boxes of diminishing size with the median (the point below which 50% of the data lie) shown as a line in the centre box. Outlying points beyond the one percentile box are shown as 'whiskers'.

Engineering Geology of the Bedrock Formations

In this section the bedrock is discussed in terms of engineering geology units (Table 6) rather than stratigraphic ones; firstly, because of widespread lithological similarities between geological formations in the study area, and secondly because, in many cases, insufficient geotechnical data are available to characterize individual stratigraphic units in isolation.

Mudrocks and Clays

Argillaceous rocks and soils constitute an important proportion of the bedrock in the study area. The geological classification of mudrocks is based predominantly on grain size (Taylor and Spears, 1981). Distinction between 'rock' and 'soil' is taken to be a function of the degree of induration (bonding and cementation) and subsequent rebound history (Cripps and Taylor, 1981). Geologically, no distinction is made between mudrocks and overconsolidated clay, although geotechnically this distinction is real though difficult to define. Attempts have been made (Grainger, 1984; Taylor and Spears, 1981 *inter alia*) to classify mudrocks by grain size, strength, mineralogy, and fabric. However, with the possible exception of strength, it is precisely these properties which largely are ignored by most site investigations. A simple first step in classification would be a division into 'durable' (i.e. capable of withstanding disintegration during cycles of wetting and drying),and 'non-durable', followed by a division of non-durable at the boundary 'very stiff cohesive soils' and 'very weak mudrock' (Grainger, 1984); this latter division being placed at an arbitrary strength value of 300 kPa.

The Mercia Mudstone has been well researched and usually is described in the literature as a heavily overconsolidated clay, although weathering tends to remove the effects of overconsolidation. It has been divided into four weathering zones (I to IV) based on the description of their geotechnical properties (Chandler, 1969). Zone I (fresh) material may be described as a mudstone (zone I material from the database is found only below a depth of 15 m). Only 5% of the strength data for Mercia Mudstone lie above a cohesion of 300 kPa, and these samples are all described in the S.I. reports as clays rather than mudstones. Weathering of Mercia Mudstone causes structural changes to the material, which modify the behaviour of samples during triaxial and consolidation tests (Cripps and Taylor, 1987). Triaxial samples classed as weathering zone IV all have values of cohesion <120 kPa. Unweathered clay (zone I) tends to exhibit brittle failure at low strains, whereas weathered clay exhibits a more plastic type of failure with a lower elastic modulus. Mercia Mudstone is also prone to structural 'collapse' (a phenomenon known as metastability) when compressed beyond a 'threshold' stress; this is particularly the case for zone II clay.

The use in site investigation reports of the terms 'marl' and 'marl rock' to describe weathered Mercia Mudstone is very common but ambiguous. Most of the Mercia Mudstone has a carbonate content less than 35%, and is not technically 'marl'. Fookes and Higginbottom (1975) recommend the following definitions based on carbonate (CO_3) content: 0 to 5% = 'claystone'; 5% to 20% = 'marly claystone'; 20 to 35% = 'clayey marlstone'.

Mudstones and clays, including the Mercia Mudstone, are frequently described as 'fissured'. Joints or fissures are planar discontinuities; those produced by stress relief tend to be sub-horizontal, whereas those due to water content changes are random in orientation. Zone III Mercia Mudstone, the most common weathering zone encountered in the database, is characterized by an abundance of 'lithorelicts', or 'floaters'; that is, inclusions of relatively unweathered parent rock (Chandler, 1969). Zone IVb (fully weathered) Mercia Mudstone, encountered particularly on low-lying boggy areas, contains no lithorelicts, but is a plastic, silty clay with some fissuring.

Compressibility of typical zone III Mercia Mudstone is low to moderate, within normally applied stress ranges (Mv typically class 3), but this is achieved at a reasonably rapid rate (Cv typically class 3). Deformation moduli for Mercia Mudstone from pressuremeter, plate bearing and oedometer tests are described in detail by Meigh (1976) and Hobbs (1975).

An important feature of the Mercia Mudstone is the occasionally high sulphate content associated with gypsum. The higher sulphate values (classes 3 to 5; Table 7c) require the use of special cement and protective coatings wherever concrete makes contact with the ground or groundwater. Some gypsum nodules are also reported within mudstone bands in the Bromsgrove Sandstone. Residual strength tests (which measure the 'minimum' strength on shear surfaces) for Mercia Mudstone, though not represented in the database, are described by Chandler (1969). The results demonstrate the dependence of residual strength on the state of weathering.

Mudstones are also found in the Bromsgrove Sandstone, Ashow, Kenilworth Sandstone, Tile Hill Mudstone, Coventry Sandstone, Keele, Halesowen and Etruria Marl formations. With the exception of the Halesowen and Etruria Marl formations, these mudstones are all lithologically very similar, and, except for the lack of gypsum, do not differ greatly from the Mercia Mudstone. As compared with Mercia Mudstones, however, they tend to be more indurated, with higher proportions of silt and sand, and more variable amounts of carbonate and, therefore, show more variation in their geotechnical properties. Pyrite is not common in these mudstones.

The pre-Triassic mudstones have undergone greater tectonization than those of Triassic or Jurassic age. This has resulted in greater fissility and shearing, which causes the rock to break up more readily on exposure or in cores, and affects the mass engineering properties. The Mercia Mudstone, in contrast, tends to have a 'block' structure, with fairly regularly spaced joints. Leaching of gypsum bands in the Mercia Mudstone extends to considerable depths (c. 15 m), and may result in significant volume changes, disturbance and loss of strength. This phenomenon is absent in the other mudstones, and 'fresh' rock profiles are encountered much nearer to outcrop, with zone IV weathering probably confined to the upper one metre.

Table 4 Engineering Geology: Summary Statistics

	Moisture content %	Liquid limit %	Plastic limit %	Bulk density Mg/m^3	Dry density Mg/m^3	% Clay	% Silt	% Sand	Undr. cohesion kPa	SPT N	Max dry density Mg/m^3	Opt. wtr. content %
Alluvium	23.8	36.6	18.7	1.92	1.54	2	9	36	50	32.5		
	(18)	(34)	(18)	(2)	(1.67)	(0)	(6)	(36)	(29)	(26)		
	14.3	13.2	5.6	0.24	0.33	4.8	9.0	25.2	60	24		
	66	68	26	1.0	1.11	19	31	89	248	80		
	63	43	43	38	30	30	36	30	30	25		
Glacial Sand	19.7	42	19.4	1.94		2	7	58				
and Gravel	(16)	(34)	(19)	(1.98)		(0)	(4)	(57)				
(undiff.)						3.3	8.4	27				
	45	55	22	0.37		13	33	94				
	18	11	11	8		50	50	52				
Wolston Clay	22.3	54	20	2.03	1.71				121			
	(22.2)	(53)	(21)	(2.05)	(1.70)				(110)			
	4.7	16	4	0.13	0.16				73			
	33	65	18	0.86	0.85				338			
	125	86	86	108	39				100			
Laminated	19.7	34.8	18	2.05					90			
Clay (undiff.)	(20)	(32)	(18)	(2.07)					83			
	14	31	7	0.19					41			
	15	15	15	6					5			
Boulder Clay	16.9	35.5	16.7	2.12	1.82				161	161	1.87	14.6
	(16)	(34)	(16)	(2.13)	(1.84)				(140)	(42)	(1.88)	(14)
	4.1	8.7	3.4	0.11	0.11				107		0.08	2.6
	43.3	86	43	1.16	0.88				690	661	0.3	11
	342	284	284	252	175				219	14	33	33
Baginton	11.6					1	5	69			1.99	9
Sand and	(13)					(0)	(4)	(71)			(2.06)	(9)
Gravel												
	9					10	13	74			0.39	4
	9					8	8	8			5	5
Mercia	20.0	35.0	19.8	2.06	1.69	1	2.6	69	126	134	1.84	16
Mudstone	(19)	(34)	(19)	(2.07)	(1.7)	(0)	(0)	(84)	(108)	(98)	(1.84)	(16)
	6.9	7.5	3.8	0.12	0.18				91	111		
	68	68	25	0.57	0.97	3	13	78	560	642	0.16	4.4
	282	241	241	182	145	5	5	5	172	83	10	10
Bromsgrove	15.3	31	16.7	1.94						64		
Sandstone	(14)	(32)	(16)	(1.93)						(67)		
	10	19	10	0.4						58		
	16	6	6	7						9		
Ashow	16.9	33	17.7	1.33								
Formation	(18)	(32)	(18)	(1.96)								
	4.9	7.0	1.9									
	19	28	7	0.44								
	30	27	27	16								
Kenilworth	16.7	35.1	18.2	2.05								
Sandstone	(16)	(34.5)	(19.5)	(2.06)								
	4.3	11.8										
	20	46	10	0.25								
	18	14	14	6								
Tile Hill	16			2.07								
Mudstone	(17)			(2.05)								
	9			0.16								
	5			5								
Coventry	16.2	34.8	17.8	2.11	1.85	8.3	30.7	59.9	120	286	1.93	12.3
Sandstone	(16)	(35)	(18)	(2.12)	(1.84)	(7)	(22)	(64)	(99)	(177)	(1.92)	(12)
	4.7	7.8	2.8	0.10	0.14	9.3	21.9	21.8	86	272	0.07	1.6
	40	40	20	0.76	1.12	43	67	93	372	951	0.34	7.1
	432	345	345	166	130	22	23	40	136	136	60	60
Keele	16.4	35.6	17.3	2.10	1.85	4.5	18.2	71.3	115	330		
Formation	(16)	(36)	(17)	(2.12)	(1.86)	(4.5)	(16)	(74.5)	(83)	(170)		
	4.6	7.2	2.5	0.12	0.14				92			
	28	45	16	0.58	0.5	10	31	46	324	849		
	116	97	97	46	42	6	6	6	55	19		

Notes:

Data Sets containing less than 5 points are not included

Standard deviation not listed for data containing less than 20 points

Key:

23.8 ← Arithmetic Mean
(18) ← Median
14.3 ← Standard Deviation
66 ← Range
63 ← Number of Data points

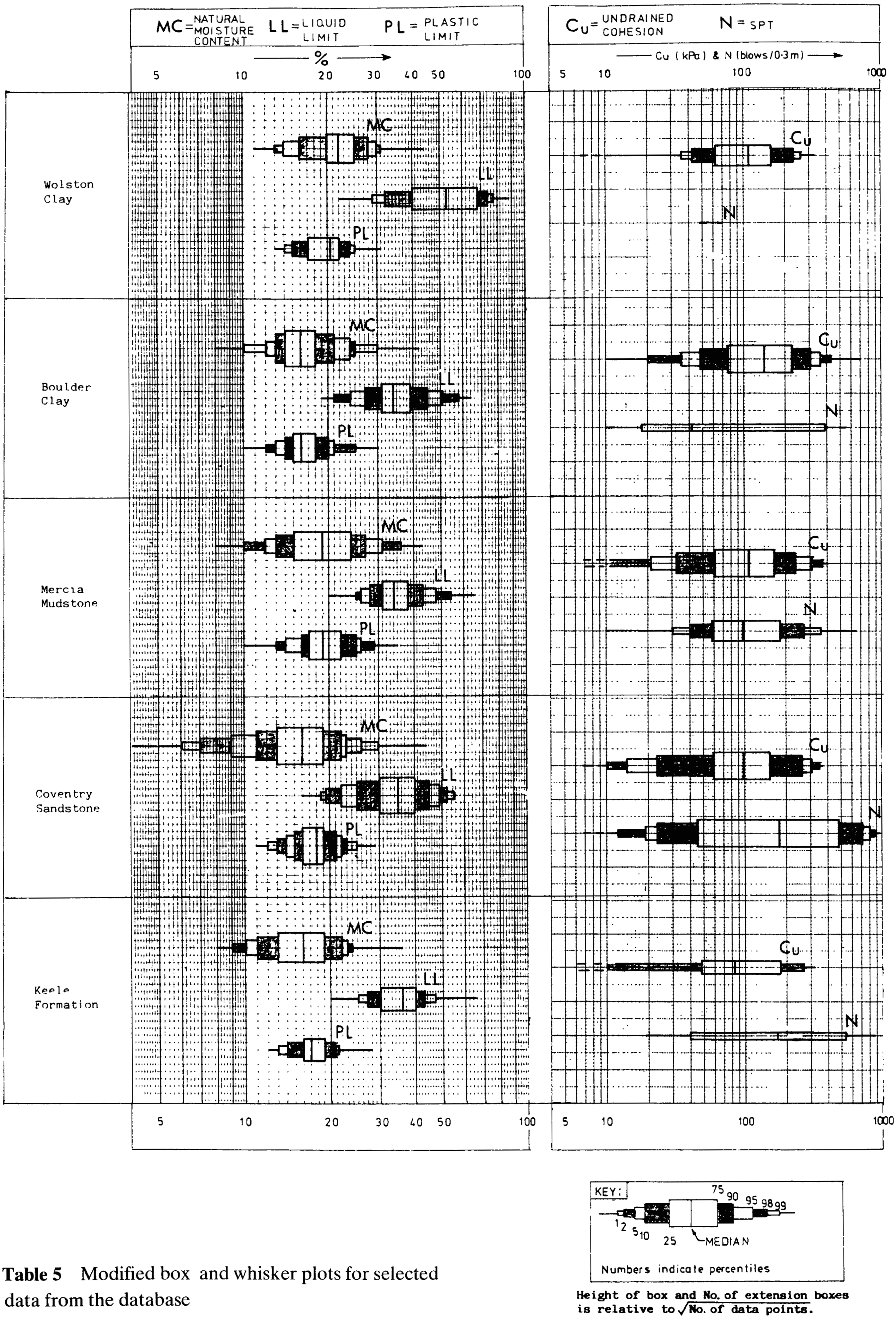


Table 5 Modified box and whisker plots for selected data from the database

Table 6 Engineering Geological Units

	Engineering Geology Unit	Stratigraphic Name
SUPERFICIAL (DRIFT)	Normally consolidated cohesive & loose non-cohesive deposits (fluvial)	Alluvium River Terrace Deposits
	Normally to slightly overconsolidated cohesive soils (glacial lake clays)	Glacial Lake Deposits Wolston Clay (+bands within Sand & Gravel)
	Heterogeneous overconsolidated/dense deposits (glacial)	Boulder Clay (undifferentiated) Thrussington Till Oadby Till (+bands within Wolston Clay)
	Dense non-cohesive deposits (glacial)	Dunsmore Gravel Fluvio-glacial Sand & Gravel Glacial Sand & Gravel Wolston Sand & Gravel Baginton Sand & Gravel
BEDROCK (SOLID)	Mudrocks/clays	Penarth Group & Saltford Shale Mercia Mudstone Group Bromsgrove Sandstone Ashow Formation Kenilworth Sandstone Tile Hill Mudstone Coventry Sandstone Keele Formation Halesowen Formation Etruria Marl Formation
	Sands/sandstones/ conglomerates	Arden Sandstone skerries within Mercia Mudstone Bromsgrove Sandstone Ashow Formation Kenilworth Sandstone Tile Hill Mudstone Coventry Sandstone Keele Formation Halesowen Formation Etruria Marl Formation
	Limestones	Lower Lias Penarth Group *Spirorbis* limestone in Keele & Halesowen Formations

Table 7(a) Coefficient of Volume Compressibility, Mv

Class	Description of compressibility	Mv (m^2/MN)	Examples
5	Very high	>1.5	Very organic alluvial clays and peats
4	High	0.3–1.5	Normally consolidated alluvial clays, eg. estuarine clays
3	Medium	0.1–0.3	Fluvioglacial clays, Lacustrine clays
2	Low	0.05–0.1	Boulder clays
1	Very low	<0.05	Heavily overconsolidated 'boulder clays'. Stiff weathered rocks

After Head (1982)

Table 7(b) Coefficient of Consolidation, Cv

Class	Cv m^2/year	Plasticity Index Range	Soil Type
			CLAYS
1	<0.1	>25	Montmorillonite
2	0.1–1		High plasticity
3	1–10	25–15	Med plasticity
4	10–100	15 or less	Low plasticity
5	>100		*SILTS*

After Lambe and Whitman (1979)

Table 7(c) Sulphates in Soils and Groundwater

Class	Total SO_3 (%)	SO_3 in 2:1 soil:water extract (g/l)	In Groundwater (parts/100 000)
1	>0.2		<30
2	0.2–0.5		30–120
3	0.5–1.0	1.9–3.1	120–150
4	1.0–2.0	3.1–5.6	250–500
5	>2	>5.6	>500

From: Anon (1972)

Strength and SPT profiles with depth do not reveal clear differences between the Mercia Mudstone and other mudstones; although the Coventry Sandstone and Keele Formation SPT profiles (Figures 6b and 7d) do suggest a greater strength below 6 m when compared with the Mercia Mudstone (Figure 6d).

An investigation for deep foundations in Coventry city centre (Cole and Stroud, 1976) showed that mudstone bands within the Coventry Sandstone range from hard clay to moderately weak mudstone. Whilst a trend of increasing strength with depth is just discernible in these data, individual mudstone bands, even at depths exceeding 20 m, may be as weak as those near the surface.

Sandstones

'Sandstone' lithologies in the study area vary widely from very strong, massive and cemented, to weakly-cemented, friable and flaggy, and include several bands of conglomerate and breccia. Weak sandstones have properties which range from the soil-like behaviour of sands to the rock-like behaviour of sandstone. Their geotechnical properties often cause problems in design and construction, and they are difficult to sample and test (Dobereiner and de Freitas, 1986). All the 'sandstones' in the database fall into the category of weak sandstones, that is with a shear strength less than 250 kPa. Strong sandstones, such as those found within the Arden Sandstone, Keele Formation, Coventry Sandstone and other formations, are not represented in the database. Additionally, very few particle-size analyses are reported, thus making classification of these rocks difficult.

The sandstones are frequently cemented by iron oxides and secondary quartz, which breaks down on weathering to leave a soil with a weak sand matrix, containing harder sandstone cobbles which can be excavated by hand. These 'soils' have shear strengths of between 10 and 100 kPa. Typically, weak and strong types of sandstone are interbedded, with the strong beds, often massive and current-bedded, forming prominent topographical features. The massive sandstones, in particular those found in the Keele Formation and Coventry Sandstone, are often separated into large, discrete blocks by near vertical joints, which commonly are open and, in some cases, affected by mining subsidence. Clay-filled joints, reported in the Coventry Sandstone, are an important feature when considering mass strength and permeability. Some hard sandstone bands within the Tile Hill Mudstone, Kenilworth Sandstone and Ashow Formation are calcareous, but the sandstones of the latter are generally deeply weathered and soft.

A feature of some sandstone beds is the presence of mudstone clasts and pellets (notably in the Keele Formation, Enville Group and Bromsgrove Sandstone). However, in contrast to the mudstones and clays, the geotechnical parameters of the sandstones are not strongly influenced by the mineral composition . Of greater importance to strength and deformability is the nature of the microscopic grain contacts, particularly their cementing, and the sensitivity of strength to moisture content. Test data for Bromsgrove Sandstone show a five-fold reduction of strength on saturation from a dry or near-dry state (Dobereiner and de Freitas, 1986). However, this observation is not confined to weak sandstones, but also applies to some other rock types.

Limestones

Limestone is found mainly in the Penarth Group and the Lower Lias, and as thin bands of *'Spirorbis'* limestone, or as calcrete soil horizons, within the Coventry Sandstone, Keele and Halesowen formations. No geotechnical data were available for the limestones.

Engineering Geology of the Superficial (Drift) deposits

The drift deposits of the study area have been divided into engineering geology units having similar geotechnical characteristics (Table 6).

Heterogeneous overconsolidated/dense deposits

Included in this unit are boulder clays (tills), such as the Thrussington and Oadby tills, and some bands within the Wolston Clay (Table 4).Typically these are relatively structureless mixtures of clasts, ranging in size from pebbles to large boulders, in a matrix of firm to hard, overconsolidated clay with some dense silt and sand. The clasts include sandstone, quartzite, mudstone, flint, coal and chalk, generally below 200 mm in mean diameter; large boulders are rare. The matrix probably represents between 70% and 90% of the deposits by volume, and they are described as 'matrix-dominant'. The deposits are characteristically very variable in composition and thickness, (usually 3 m to 5 m, but reaching a maximum recorded thickness of 18 m where they fill a 'buried' channel in the bedrock). In the east, they occur in relatively well-defined stratified units, whereas in the west, there is much more interdigitation with other glacial drift lithologies.

The engineering behaviour of these deposits is determined largely by the nature of the matrix. Overconsolidation, associated with lodgement tills, results in vertical and horizontal joint systems, and these may produce poor stability when unloaded during excavation (Fookes and Vaughan, 1987). Weathering appears to extend to only shallow depths (1 to 2 m), and involves weathering zones II and III using the four zone classification of Eyles & Sladen (1981). The resulting increases in moisture content (Figure 8a) and clay content lead to softening, and hence loss of strength. Plasticity ranges from low to high. Natural moisture contents are, on average, slightly higher than optimum moisture contents from compaction tests. As moisture content tends to increase at a greater rate than plasticity index, the liquidity index of weathered boulder clay tends to be higher than for unweathered (Sladen and Wrigley, 1983). Swelling of the clays on excavation, and any subsequent mixing with other drift, also combine to alter moisture content and strength, and may make the material unsuitable for use as fill.

Excavation within a matrix-dominant boulder clay is reasonably easy. Problems arise, however, when granular pockets and infilled outwash channels, containing running sand/silt or thixotropic sand/silt/clay mixtures, are encountered unexpectedly. The clay/bedrock boundary is unpredictable, and it may contain concentrations of granular material often holding significant quantities of groundwater, which may be under artesian pressure. Tunnelling into such glacial deposits is very difficult, as the tunnel face may be split up into two or more totally different materials, each requiring different treatment. Bevan and Parkes (1978) describe tunnelling in boulder clay using compressed air, beneath Coventry and elsewhere, and stress the importance of understanding local groundwater conditions. Careful, high quality site investigation and representative laboratory testing of these materials are essential.

Normally to slightly overconsolidated cohesive deposits

These deposits are relatively uniform, but cannot be described as homogeneous due to their marked anisotropic structure. They are largely represented in the study area by the Wolston Clay, which is subdivided in places by the Wolston Sand and Gravel.

The Wolston Clay is an almost stoneless, finely-laminated, brown, slightly calcareous, silty clay up to 15 m thick. Laminae and lenses of sand, and bands of stony boulder clay occur. Steeply dipping laminae, recorded in one report, are possibly due to subsidence during melting of ice or glaci-tectonics. The clays range in consistency from firm to stiff, becoming soft near the surface and hard at depths >10 m. In the absence of mineralogical data the reasons for the high plasticity recorded in some investigations (Figure 9b) are not clear. However, Taylor and others (1976) give moderately high mixed-layer (expanding) clay mineral contents for Devensian laminated clays. Moisture contents exceed 30% only in the upper 2 m (Figure 8b). Strengths are generally lower than for boulder clay (Figure 10c), but suggest moderate overconsolidation or possibly pseudo-overconsolidation. Secondary water tables, due to granular bands within the clays, may in some situations be slightly artesian. An important engineering characteristic of laminated glacial lake clays, which is not quantified in the database, is their anisotropy, which results in wide differences of drained strength and permeability values, depending on the direction of loading and water flow, respectively. Consolidation or swelling rates tend to be rapid in the horizontal direction.

Dense non-cohesive deposits

These deposits include the Baginton Sand and Gravel, Glacial Sand and Gravel (undifferentiated), the Wolston Sand and Gravel (within the Wolston Clay) and the Dunsmore Gravel. Particle size distributions (Figures 11c and 12b) show similar gradings for Baginton Sand and Gravel and the undivided glacial sand and gravel unit. Both are well sorted, but the data presented here (Figure 11c) are more widely scattered than those from Crofts (1982) which relate to the south-east part of the study area. The Baginton Sand and Gravel commonly consists of a sand unit overlying a sand and gravel (Plate 1). Differences in lithology between the various named units are marked (Figures 12a and 12c).

Both the Glacial Sand and Gravel and Baginton Sand and Gravel units have been worked in the past. Of the various units, the Baginton Sand and Gravel is probably the most suitable as concrete aggregate, due to its low ironstone, flint, sandstone and limestone content. The undifferentiated Glacial Sand and Gravel and the Dunsmore Gravel have higher contents of potentially deleterious 'unsound' lithologies such as ironstone and flint (Dunsmore), and mudstone (Glacial Sand and Gravel).

Normally consolidated cohesive and loose non-cohesive deposits

River terrace deposits and alluvium constitute relatively minor components of the drift. The former are concentrated in the Avon, Sowe and Blythe valleys, and are divisible into four terraces. Because relatively little information was available for alluvium, the two are combined in the database (Figures 9c, 9f, 10b and 21b), although some separated data are presented by Crofts

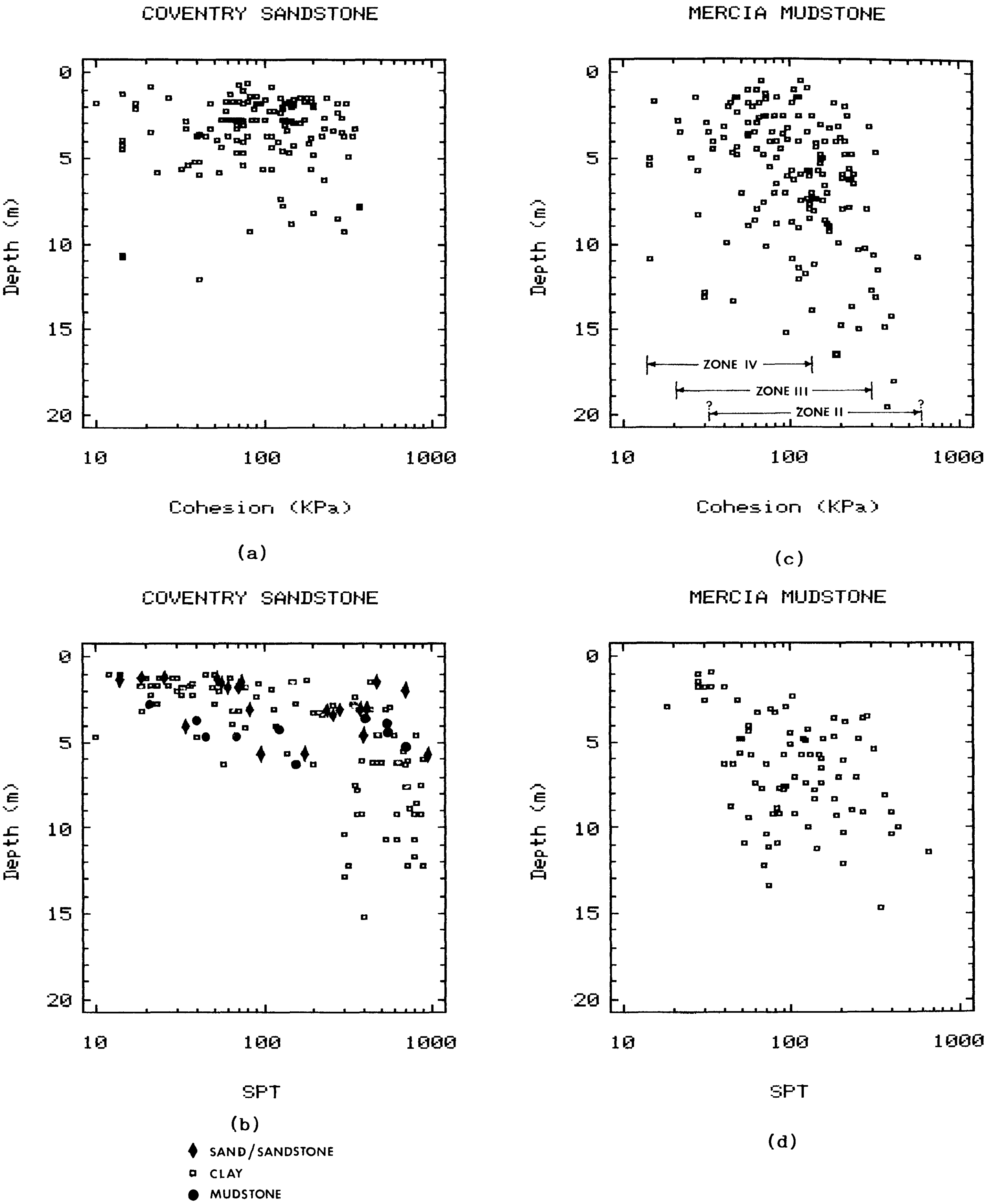


Figure 6a-d Cohesion and SPT values for Coventry Sandstone and Mercia Mudstone

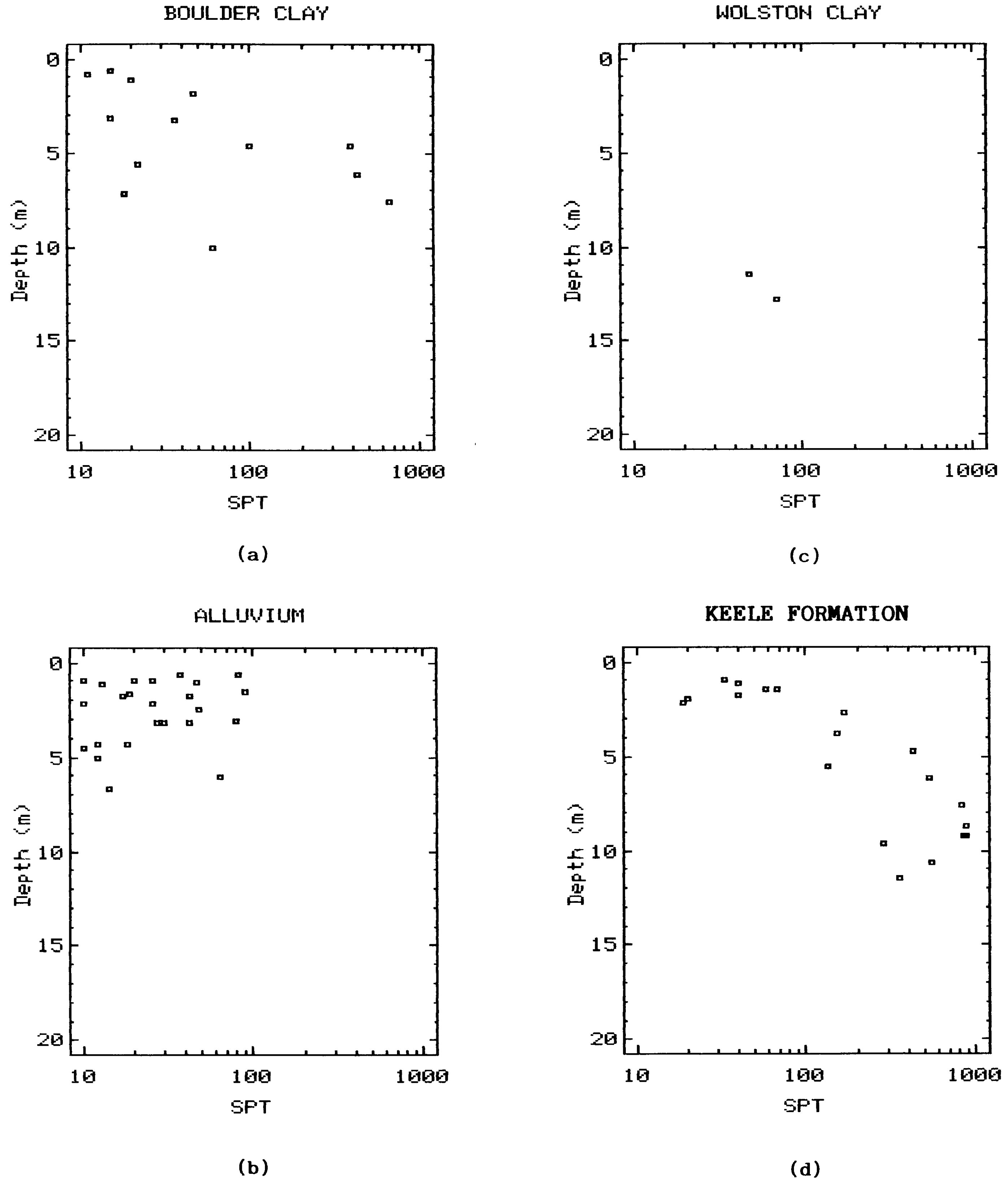
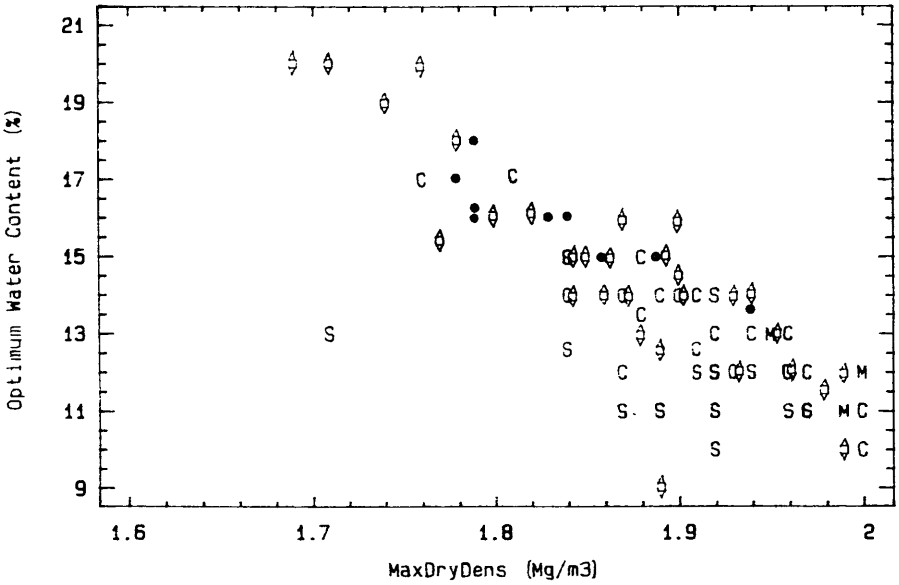
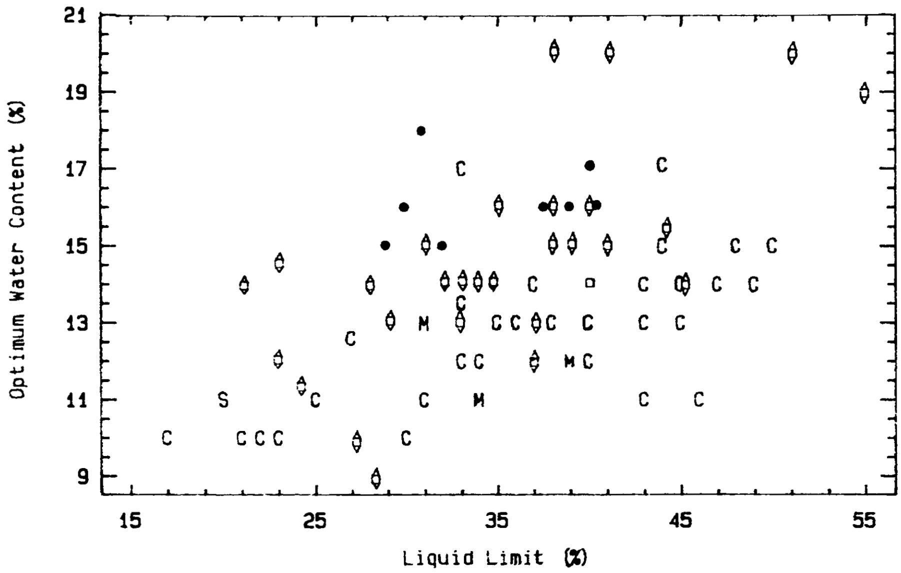


Figure 7a-d SPT values for Boulder Clay, Alluvium, Wolston Clay and Keele Formation



(a)



(b)

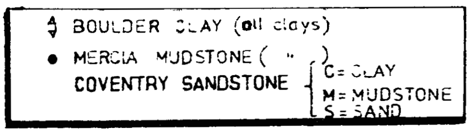


Figure 8a Optimum water content vs Maximum dry density. **b.** Optimum water content vs Liquid limit for Boulder Clay, Wolston Clay and Alluvium

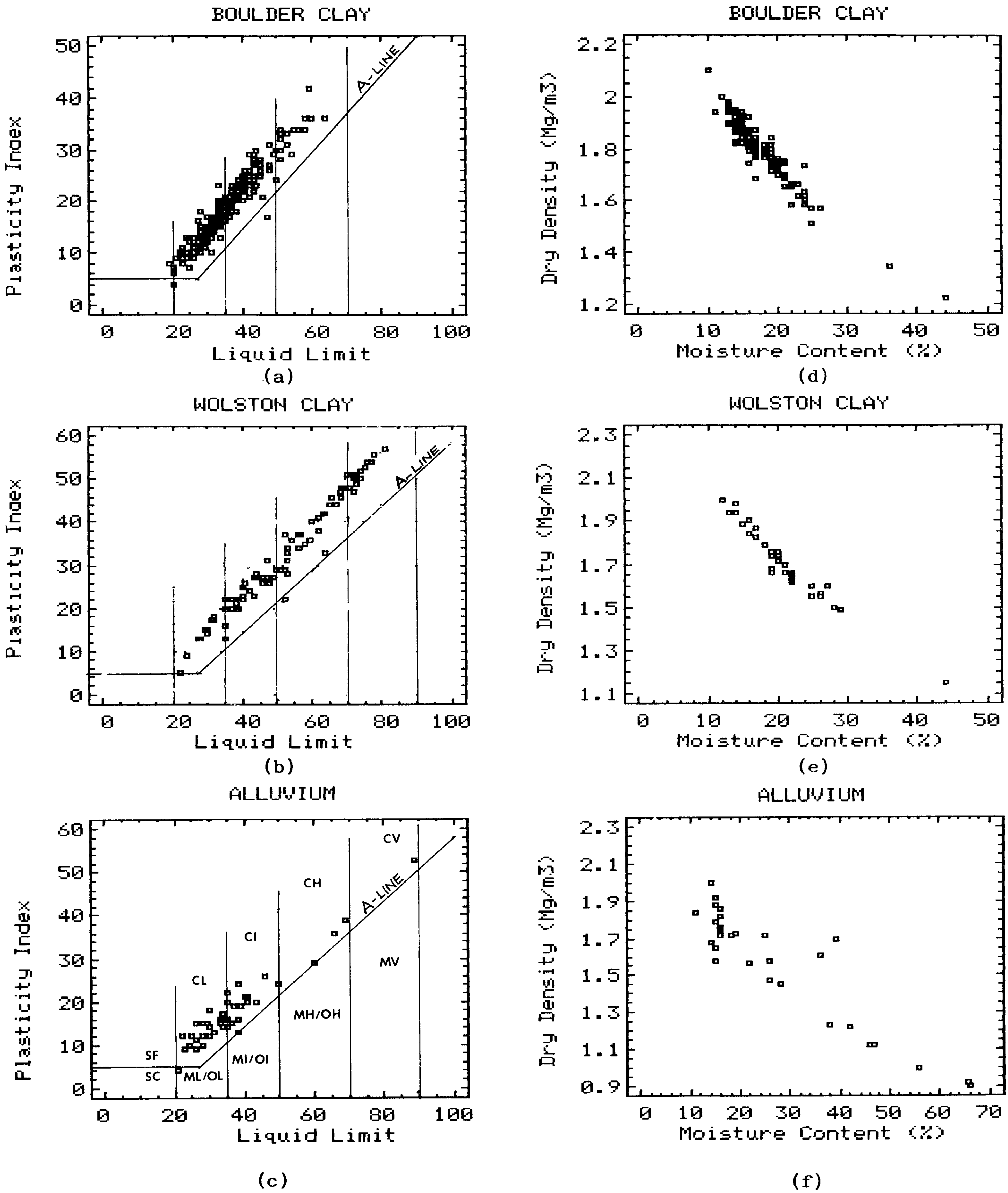


Figure 9a-c Plasticity index vs Liquid limit for Boulder Clay, Wolston Clay and Alluvium. **d-f** Dry density vs Moisture content for Boulder Clay, Wolston Clay and Alluvium

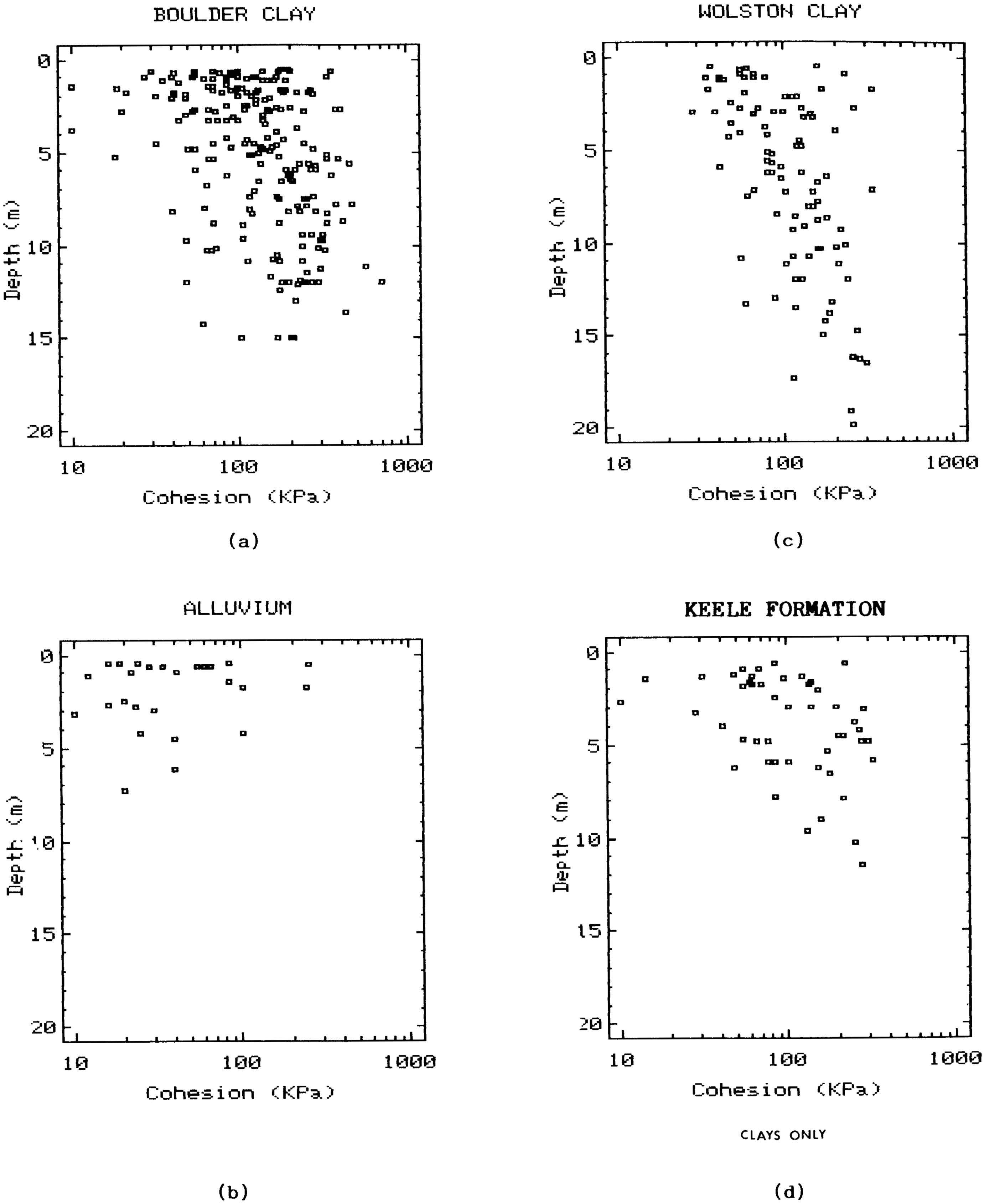


Figure 10a-d Depth vs Cohesion for Boulder Clay, Alluvium, Wolston Clay and Keele Formation

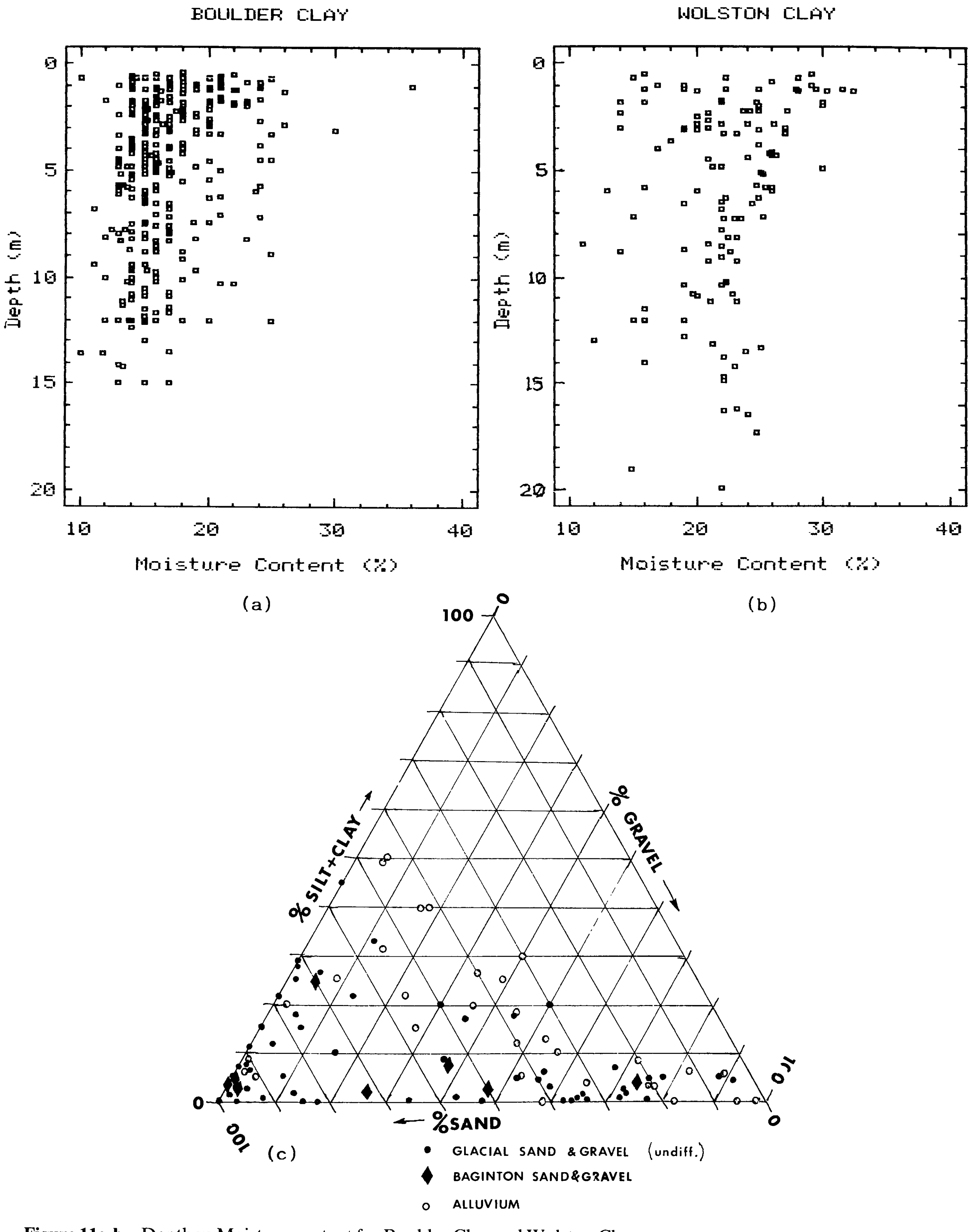
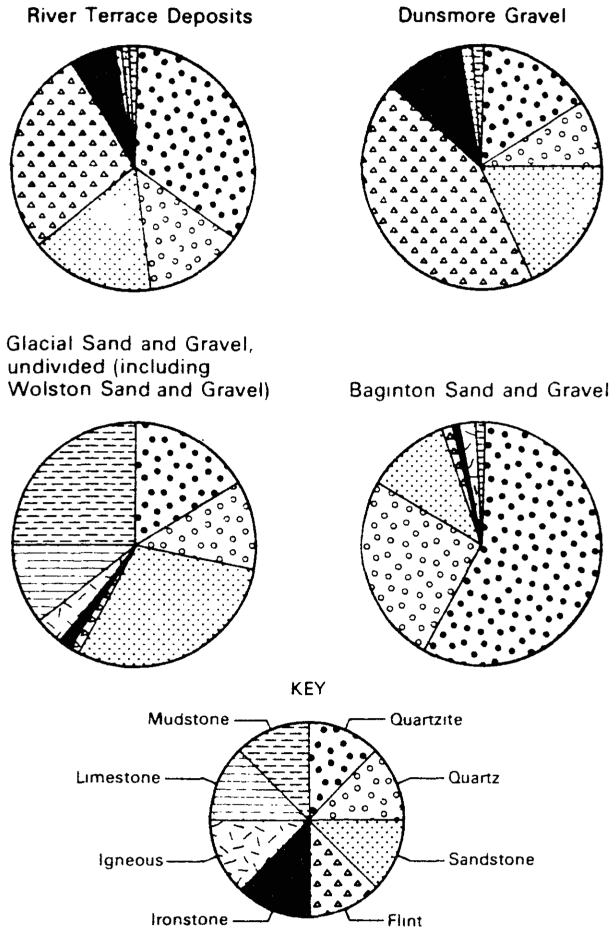
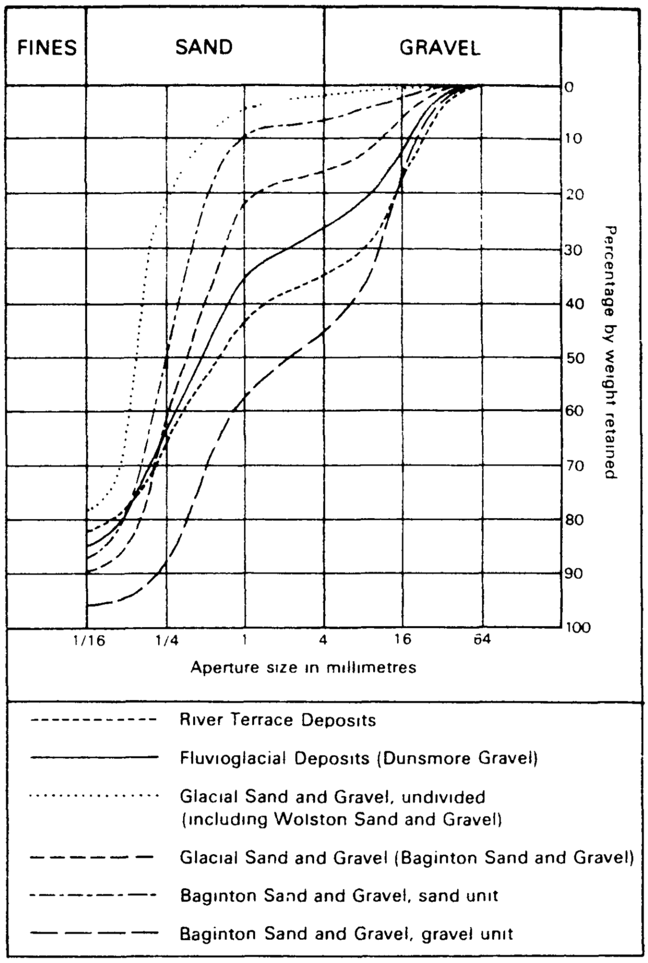


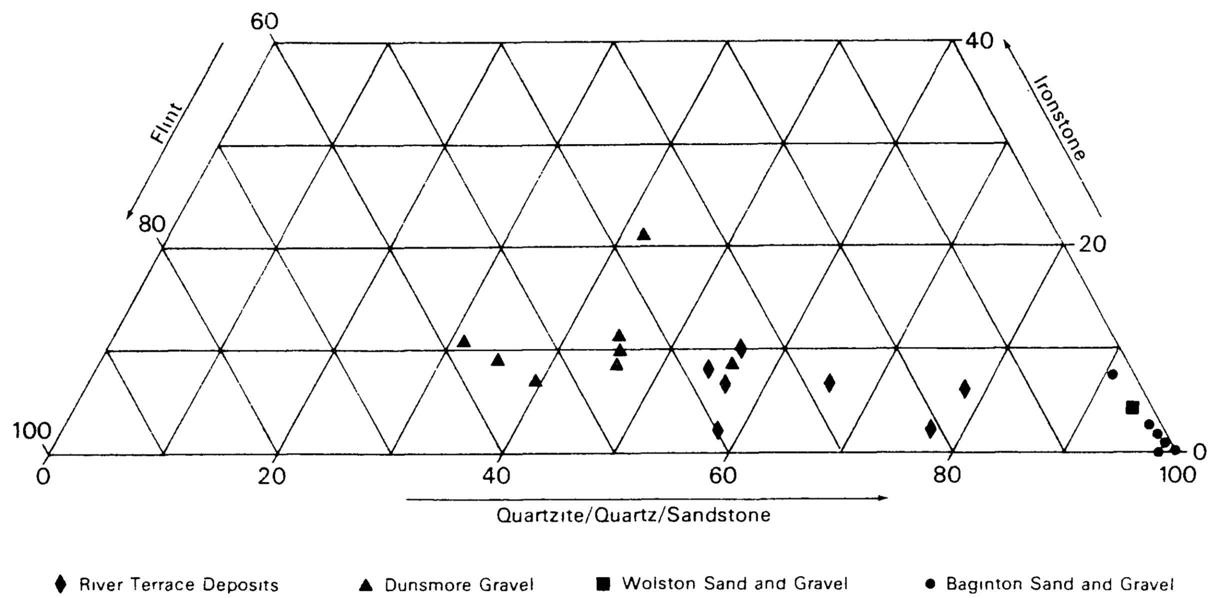
Figure 11a-b Depth vs Moisture content for Boulder Clay and Wolston Clay.
c Particle size distribution for sand and gravel deposits



a. Mean lithological composition of +8 -16mm fraction of sand and gravel deposits (based on weighted means from selected boreholes)



b. Grading characteristics of the sand and gravel deposits



c. Lithology of +8–16mm fraction from individual IMAU samples, expressed as percentages of flint, ironstone and of quartzite, quartz and sandstone combined.

Figure 12a-c Mean lithological composition, grading characteristics and lithology of sand and gravel deposits

(1982). For these limited data, a wide scatter is found throughout, including the index and strength test results. The strength of alluvial soils is generally low, while compressibility is high, and moisture content occasionally high (Figure 9f). In general, strength decreases and compressibility increases with increasing fines content. Alluvium with a high silt and sand content is subject to erosion and piping. Undrained cohesion (Figure 10b) is useful when considering short-term stability of foundation loading, but is not appropriate for drained or long-term unloading stability of excavations or cut slopes.

The few beds of peaty or organic clay within the alluvium are not represented in the database. They are noteworthy due to their very high compressibility, and are subject to long term creep. They yield low pH values (around 4 to 5).

Head, Colluvium and Landslip deposits

Large, easily identified landslips, occurring as localised features of steep slopes, can pose major problems to engineering works, and have been well described in terms of mapping, stability analysis and remedial measures (Hutchinson, 1988). Such landslips have not been recorded in the study area. Smaller, and degraded slips are less well documented, even though they too may cause engineering hazards. More common, though equally less well documented, are occurrences of shallow-angle slope instability with little surface expression.

Head or colluvium is a sheet-like deposit of solifluction debris, derived from underlying or adjacent bedrock or drift, and mobilized on a slope by periglacial freeze-thaw action. It has only been mapped locally and probably only rarely exceeds 2 m in thickness in the study area. It is not described in the site investigation reports contributing to the database. Head may be difficult to distinguish from the deposits from which it is derived. However, its presence should be anticipated, because it may be potentially unstable on slope angles as low as 5°, and movement may be re-initiated by engineering works.

Spatial distribution of Head is characteristically unpredictable and it is commonly found infilling troughs and hollows in the underlying bedrock or drift. The geotechnical differences, between Head and the bedrock from which it is derived, are measurable in terms of reduced strength, increased moisture content, and the possiblility of one or more very weak slip planes, within or at the base of the deposit.

On steeper slopes a highly weathered mantle of bedrock or drift may slip gradually downslope by a process known as creep, whilst on shallower slopes flow-type landslips may develop or be re-activated in highly plastic saturated clays. These types of slip are usually shallow but, as with Head, may present problems to the engineer. In the study area no such landslips are recorded, though they occur in the Penarth Group and the Wolston Clay to the south-east (Old and others, 1987). The Wolston Clay includes high plasticity clays which on slopes steeper than about 8° to 10° may be considered potentially unstable.

Fill and Made Ground

Man-made deposits are widespread, particularly in industrial and urban areas, and are described elsewhere in the report. The variety of fill material is so great that it is virtually impossible to characterize as a deposit. It includes building rubble, industrial and domestic waste, mining spoil, chemical and toxic material, and soil and rock from civil engineering works, each of which presents its own problems (Bell, 1978). Fill is often highly compressible, inconsistently compacted, deleterious to building materials; it may contain pollutants, and may generate noxious or explosive gases. Sometimes considerable thicknesses of fill occur (up to 8 m are recorded in the database), and may require piled foundations, depending upon the structure and the nature of the fill. One phenomenon highlighted by engineering investigations in and around Coventry, is the presence of infilled craters caused by high explosive bombs during World War 2. These may be bounded by disturbed soil or fractured rock (Geotechnics Ltd. pers.comm.).

CONCLUSIONS AND RECOMMENDATIONS

New geological maps and a revised stratigraphy have been produced for the Coventry area. These provide the basis for the thematic geological maps, the assessment of mineral resources and hydrogeology, and the interpretation of the geotechnical database.

CONCLUSIONS

Geology

The new 1:10 000 geological maps and the accompanying open file reports, provide the most up-to-date geological information that is available for the study area. The published data will be of direct relevance to the coal mining, sand and gravel and water industries, and will provide a geological framework for land-use and planning considerations.

Cambrian

The new palaeontological data presented for the Cambrian has provided preliminary evidence for the structure of these deeply buried rocks.

Carboniferous and Permian

Detailed mapping of the outcropping formations, combined with borehole, seismic, mining and palaeontological data, has greatly improved the knowledge of the stratigraphy and structure of these rocks.

The subdivision of the Keele Formation, and the establishment of formational boundaries in the Enville Group, represent important advances on the previous geological maps. Even for those formations which are entirely or largely concealed, lithological and palaeontological correlations have been established, and the uncertainty regarding the identification of the Halesowen/Keele boundary has been highlighted.

Triassic

Interpretation of two deep boreholes in the Knowle Basin has proved the existence of thick Triassic deposits, which are unknown at outcrop in the study area. This interpretation, when integrated with the evidence provided by the mapping of skerry bands in the Mercia Mudstone, has revealed major growth faults bounding the eastern side of the Knowle Basin.

Quaternary

The study has proved the existence of extensive outcrops of glacial drift, which were not shown on pre-existing geological maps. Mapping of the various glacial deposits, and identification of the erratics within them, has provided a fuller understanding of the glaciation of the area.

Large outcrops of river terrace gravels, shown as boulder clay on previous maps, have been discovered near Coleshill.

Thematic Geological Maps

The thematic maps present overviews for the selected themes, and provide non-specialist users with easily understandable data regarding bedrock and drift geology, mineral and water resources, underground mining and boreholes.

Engineering Geology

The geotechnical database has been interpreted to provide a general guide to the geotechnical properties of the various bedrock and drift formations, and Appendices II and III provide further information for those needing a fuller explanation of the data, or of the geotechnical tests.

RECOMMENDATIONS

To improve the existing geological database would require a considerable capital outlay but, especially in the case of the deeply buried rocks, the benefit to the national economy might be considerable.

The deeply buried rocks, either within the Knowle Basin or beneath the Productive Coal Measures of the Warwickshire Coalfield, are not known in detail. A considerable amount of seismic and borehole geophysical data held by British Coal for these areas has not been fully interpreted. While there may be some justification for preserving the confidentiality of these data, it is recommended that summaries should be released to the wider geological community, or that funds should be provided to the British Geological Survey to purchase and interpret them.

An east-west seismic profile across the Knowle Basin, linked in the east to existing British Coal seismic data, is strongly recommended, as this would add greatly to the understanding of the structure of the area. In particular it would provide information regarding the possible westwards continuation of the Productive Coal Measures of the Warwickshire Coalfield. Based on the evidence from the seismic line a deep borehole is needed to prove the pre-Triassic basement of the Knowle Basin, which at present is unknown.

The thickness and subsurface lithology of the newly discovered outcrops of drift are not known in detail. It is recommended that exploratory drilling should be carried out, especially in areas where future development is proposed or anticipated.

APPENDIX I GEOLOGY

CAMBRIAN

Wherever proved, the pre-Carboniferous rocks beneath the area are of Cambrian age (here taken to include the Tremadoc Series); they are assigned to the Merevale Shales (Tremadoc Series) and formations in the Merioneth Series.

Cambrian rocks have been penetrated by several boreholes (Figure 13), but only to a maximum thickness of 50 m and no detailed correlation is possible. Faunal zones proved show that the strata young into a NE-SW belt, presumed to be the northern limb of a syncline, (Old and others, 1987).

Taylor and Rushton (1971) divided the Upper Cambrian part of the Stockingford Shales of the Nuneaton Inlier as follows:

Merevale Shales	90 m	Tremadoc Series
Monks Park Shales	80 m	Merioneth Series
Moor Wood Flags and Shales	15 m	
Outwoods Shales	300 m	

The gradational passage from the Monks Park Shales to the Merevale Shales lacks a distinctive fauna, so the boundary between the Merioneth and Tremadoc series cannot be identified precisely. Above these passage beds the Tremadoc of the area includes the lowest three of the subdivisions recognised in Shropshire by Stubblefield and Bulman (1927), and continues that sequence downwards, into 'Basal Tremadoc' as follows:

Clonograptus tenellus Zone:	with *Clonograptus* and *Adelograptus* species
Transition Beds:	*Clonograptus* is interbedded with *Dictyonema*, including, *D.flabelliforme anglicum*
Dictyonema flabelliforme Zone:	*D.flabelliforme flabelliforme* and subspp. but no *Clonograptus*
'Basal Tremadoc':	lacking distinctive biostratigraphical characters

Monks Park Shales

Only the Monks Park Shales from the Merioneth Series have been proved. They include dark grey or black, fissile mudstones, as in Solomon's Temple, Fillongley and Moor Farm boreholes, or pale green siltstones as in Dove House Farm Borehole. *Orusia lenticularis* at Dove House Farm, Moor Farm and Corley Moor indicate the Zone of *Parabolina spinulosa* from the lower part of the Monks Park Shales.At Moor Farm, beds just above yielded *Leptoplastus* spp. including *L. crassicornis*, and *Eurycare ?* proving the *Leptoplastus* Zone. Solomon's Temple Borehole yielded *Broeggeria salteri* and '*Prooneotodus' tenuis* and Fillongley Borehole *B.salteri* and *Sphaeropthalmus sp.* proving the *Peltura scarabaeoides* Zone or younger beds from the upper part of the Monks Park Shales.

Merevale Shales

The Merevale Shales consist of mudstones with thin sandstone beds. The mudstones are grey, greenish grey, rarely dark grey, and in places are reddened immediately below the sub-Carboniferous unconformity. They range from fissile to massive and silty, and some contain micaceous and pyritic layers. The sandstones are generally thin (2 to 100 mm), fine grained and cross laminated. Some massive silty beds show cone-in-cone structure. Besides current structures such as ripple-drift, toolmarks and evidence of scour, the sediments show signs of penecontemporaneous soft-sediment deformation, such as small-scale load casts, graptolites deformed by mud-flow, and incipient fracture-cleavage passing laterally, within the span of the core, into polished bedding-surfaces. Bioturbation is widespread and faint burrows, commonly pyritic, occur in the mudstones. The sandstones and siltstones show horizontal sinuous burrows (some resembling *Planolites*), vertical burrows (some in pairs), trails or tracks ('footprints' of arthropods?), scratch-marks, and pellets, some of which fill burrows (*Tomaculum*). Body-fossils are rare to common in the mudstones but were not observed in the sandy interbeds. Commonest are inarticulate brachiopods, especially small *Lingulella* and acrotretids. Sponge spicules and problematical dark traces of organic origin occur widely, but trilobites and other arthropods such as bradoriids are very rare. Graptolites are common and of the greatest biostratigraphical value.

The presumed 'Basal Tremadoc' beds were proved in boreholes west of Coventry, and comprise grey and dark grey mudstones with a few thin sandstones. Fossils include sponge spicules, small acrotretids and conodonts, especially '*Prooneotodus' tenuis*. Berryfields Farm Borehole [2499 8148] yielded numerous sponge bodies as well as spicules, acrotretids resembling small *Eurytreta sabrinae*, '*Prooneotodus' tenuis*, and the trilobite *Euloma sp.*, the latter suggesting a stratigraphical level above the Monks Park Shales; an analysis of the microflora by Dr R E Turner indicated an age no younger than lowest Tremadoc.

Strata of the *Dictyonema flabelliforme* Zone typically comprise pale grey silty mudstones with numerous sandstone interbeds, as in Crewe Farm, Stareton, Black Spinney, and Southam boreholes. The *Dictyonema* are mainly those referred by Bulman (1954) to *D.flabelliforme flabelliforme*, and are generally associated with *Eurytreta sabrinae* and small *Lingulellae*, possibly *L.nicholsoni. Broeggeria, Linnarssonia cf. belti* and sponge spicules are rare, and no '*Prooneotodus' tenuis* was observed. Meriden Borehole [2682 8186] yielded *D.flabelliforme* aff. *sociale* (Bulman and Rushton, 1973, p.13), and Outwoods Borehole [2463 8528] numerous *D.flabelliforme belgicum*, some with short bithecae. The locations of these two boreholes close to subcrop of the Monks Park Shales point to a low horizon in the

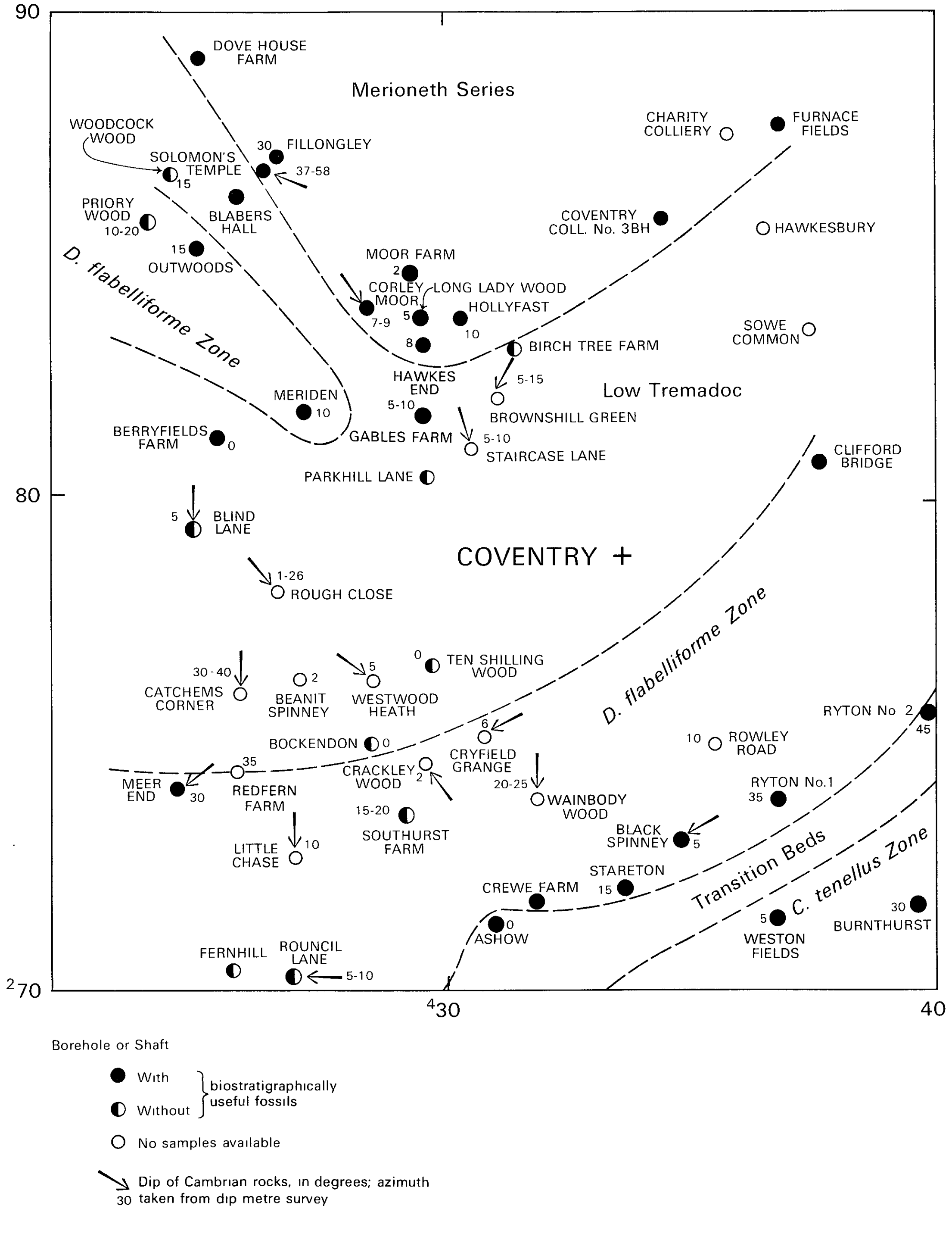


Figure 13. Cambrian faunal zones proved in shafts and boreholes

Tremadoc; hence the view that short bithecae in *D.flabelliforme belgicum* are an indicator of high Tremadoc rocks (Bulman and Rushton, 1973, p.8) is not supported, though the structure is too imperfectly known for it to be positively disproved. *D.flabelliforme patulum* occurred in Meer End and Combe Abbey No.1 boreholes.

Bulman and Rushton (1973, p.11) suggested a high Tremadoc horizon at the latter site, but a reconsideration of the associated shumardiid trilobites indicates strata below the *C.tenellus* Zone.

Grey mudstones with thin sandstones of the Transition Beds from Brandon (Ryton No.2) Borehole showed the characteristic alternations between *Clonograptus tenellus* and *D.flabelliforme anglicum*. The lithologies and the associated fauna of small *Lingulella* and rarer *Eurytreta sabrinae* most resemble those of the *D.flabelliforme* Zone. Ashow Borehole proved paler, greenish grey mudstones with fewer sandy interbeds, and with brachiopods including *Linnarssonia* cf. *belti*; one anisograptid fragment and one specimen of *Shumardia curta* were noted. This core would probably have been referred tentatively to the *C.tenellus* Zone but for the fact that *S.curta* is known only from the *D.flabelliforme* Zone and the Transition Beds.

Strata of the *Clonograptus tenellus* Zone are mainly mudstones and silty mudstones, commonly greenish grey. Sandstones are fewer than in the *D.flabelliforme* Zone, and the rocks are more fossiliferous. Of the graptolites, *C. tenellus* is the commonest, and its subspecies *tenellus, sarmentosus* and *hians* have all been found. *Lingulella* is common, being represented by small specimens, possibly of *L.nicholsoni*. Acrotretids are common, especially *Eurytreta sabrinae* and *Linnarssonia* cf. *belti*, but *E.bisecta* and *Torynelasma sp.* occur rarely. *Broeggeria salteri*, apparently thicker-shelled than those in the Monks Park Shales, occurs sporadically, and *Palaeobolus quadratus* rarely. Sponge spicules are widespread but '*Prooneotodus*' is rare, observed only at Weston Fields. Trilobites are very rare, the only determinable example being a large but fragmentary *Niobella* from the Chalet core. A curious feature of the *C.tenellus* Zone is the presence of shapeless masses of dark, apparently organic, matter, flattened along the bedding and commonly associated with chitinozoa; these chitinozoa are *Lagenochitina esthonica* (about 1 mm long) and occur singly or in chains of several individuals. These associations have not been observed at lower horizons, but occur in all the *C.tenellus* Zone cores.

UPPER CARBONIFEROUS (WESTPHALIAN) AND ? LOWER PERMIAN (AUTUNIAN)

No Viséan or Namurian strata are known within this area and the Westphalian beds rest directly on the Cambrian basement. Exploration to the north in the exposed Warwickshire Coalfield has been extended southwards and Westphalian A to Westphalian D strata are now well known beneath later cover (National Coal Board, 1985)(Figure 14) . This information supplements the older exploratory boreholes and workings from Binley Colliery (Figure 15). The Westphalian of the Coventry district has been described by Eastwood and others (1923) and Mitchell (1942); that of the Warwick district by Old and others (1987); and regional accounts of sedimentology are given by Fulton and Williams (1988) and Besly (1988).

A generalised sequence for the Westphalian and ?Autunian of this district is shown in Figure 3. The sequence consists mainly of mudstones, siltstones, sandstones and seatearths. The lower part and the Halesowen Formation are grey and coal-bearing; the Etruria Marl Formation is variegated red and green; the Keele Formation and Enville Group consist almost entirely of red measures, predominantly argillaceous in the former and predominantly arenaceous in the latter.

Westphalian (Coal Measures)

The classification of the Warwickshire Westphalian succession is shown in Table 8. The exact chronostratigraphic horizon of the base of the Westphalian succession in the south of the Warwickshire Coalfield is uncertain, but is probably within the Lenisulcata or Communis chronozones. The Westphalian A/B boundary is taken at the base of the Vanderbeckei Marine Band in the northern part of the district, but further south where the Marine Band is absent, it is placed immediately above the Thin Coal. The B/C boundary is the Aegiranum Marine Band.

Due to the paucity of both marine and non-marine faunas, a precise chronostratigraphic classification of the upper part of the Westphalian of Warwickshire is impractical at present. The horizon of the base of the Etruria Marl Formation is variable, and it is convenient to take the base of the Halesowen Formation as the base of the Westphalian D stage, which is marked by an unconformity.

Westphalian A

The thickness of Westphalian A varies between 30 and 50 m, with local increases to 75 m and decreases to 25 m. The bulk of the strata are recorded as mudstones and seatclays; in some areas sandstones and conglomerates occur in the basal few metres. The unconformity with the underlying rocks is not always obvious since the top few centimetres of the Cambrian are commonly weathered and may contain Carboniferous rootlets.

In the northern part of the Coalfield, the Westphalian A contains seams of coal – notably the Thin, Seven Feet and Bench. The recent exploration has shown that these are thin and impersistent in the south, and positive seam identifications are not feasible due to the paucity of recorded non-marine markers. The succession is characterised by abundant seatearths, many of which are brownish or putty-coloured, with abundant sphaero-siderite, for which deposition close to the landward margin of the coal-forming delta with frequent emergence is indicated.

Westphalian B

The Westphalian B includes the highest normally productive measures of the Warwickshire Coalfield, (but see Halesowen Formation). The thickness of the beds varies from about 55 m to 70 m.

Measures below the Thick Coal

These measures consist of seatclays and mudstones, usually with dark mudstone towards the base. They are

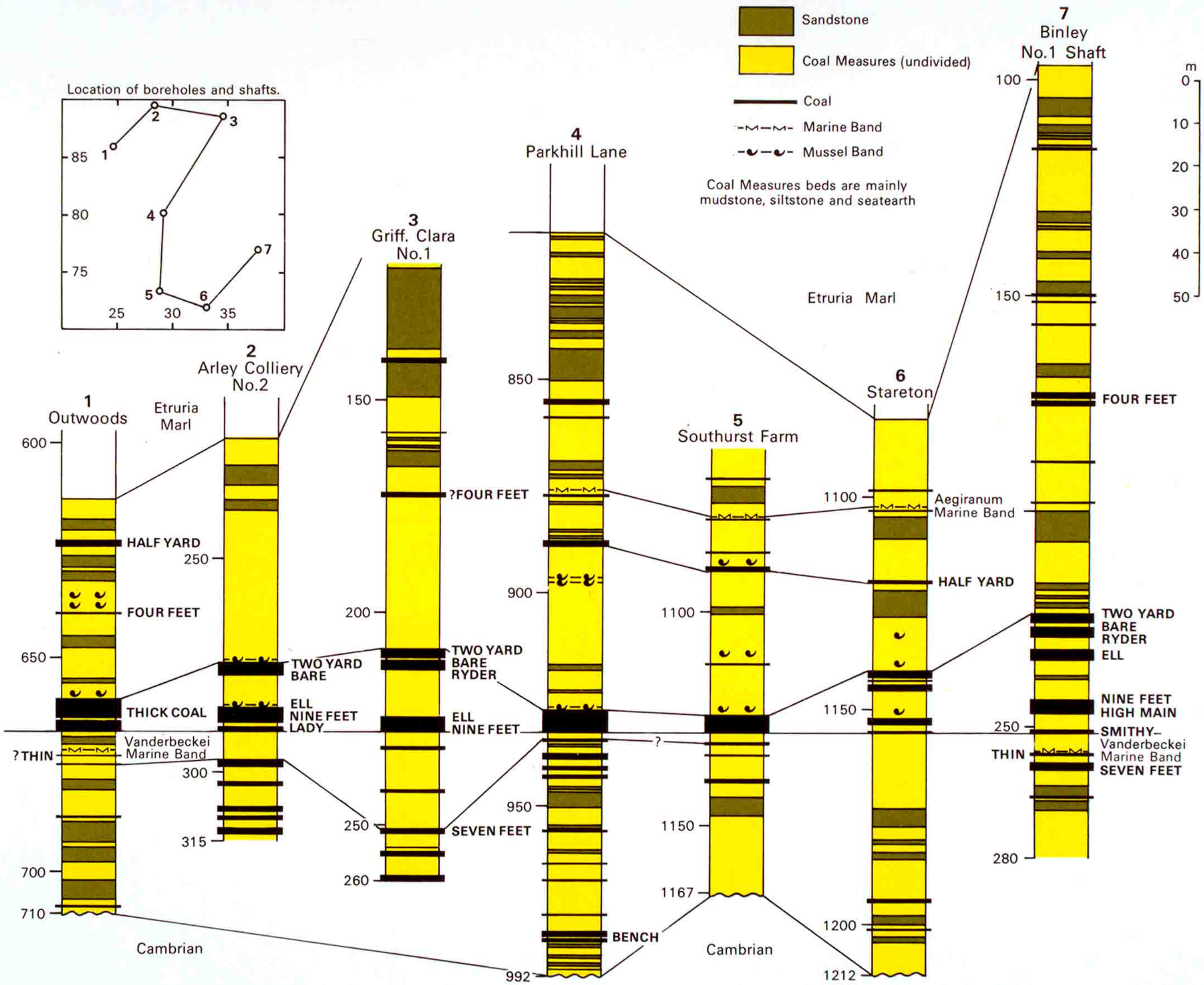


Figure 14. Comparative sections of the Productive Coal Measures

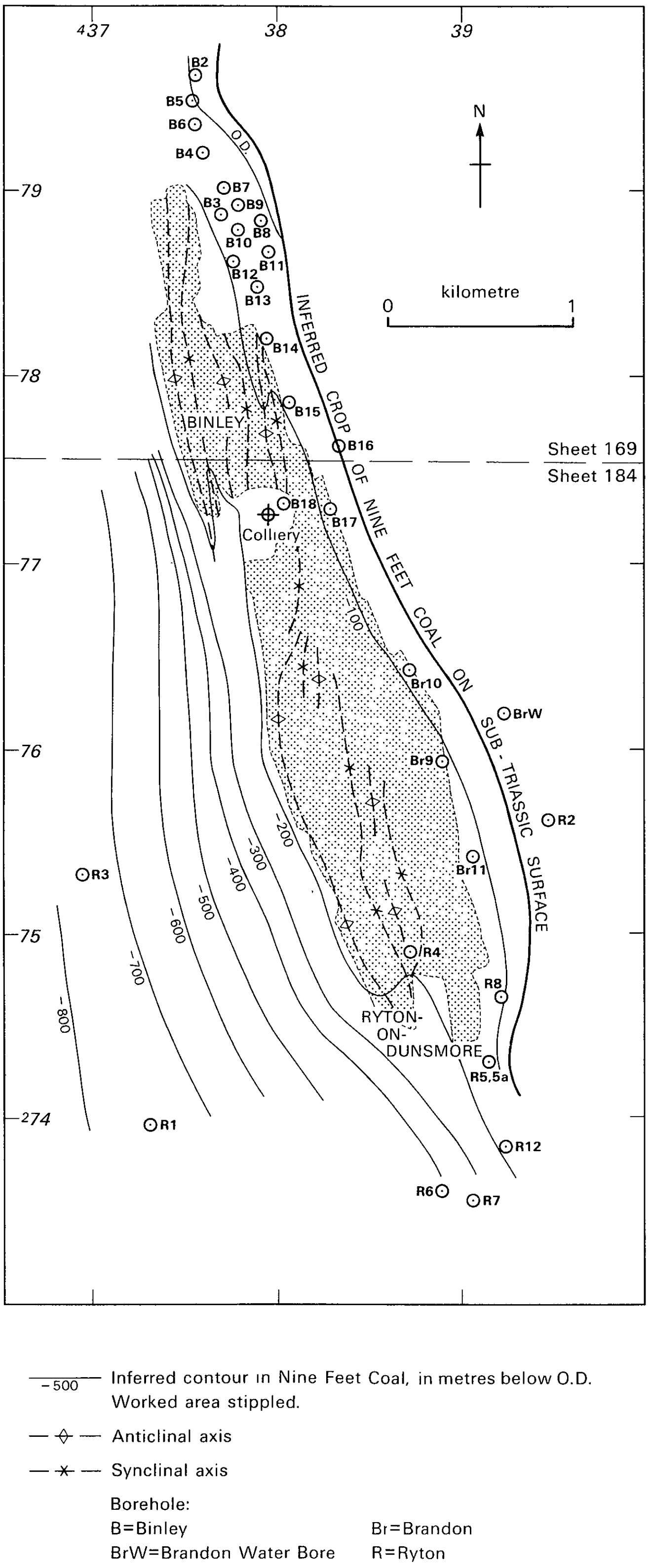


Figure 15. Binley Colliery: structure contours on Nine Feet Coal

Table 8 Classification of the Westphalian of the Warkwickshire Coalfield (in part based on Ramsbottom and others, 1978, pls.1–3)

Stages	Non-Marine Bivalve Zones (Trueman and Weir, 1946)	Marine bands	Warwickshire succession	Lithostratigraphic divisions: Mitchell (1942)	Lithostratigraphic divisions: Stubblefield and Trotter (1957)
D	Prolifera Tenuis		Enville Group (part) Keele Formation Halesowen Formation	Upper Coal Measures	Upper Coal Measures
C	Pillipsii	Cambriense	Etruria Marl Formation		
	Upper Similis-Pulchra				
B	Lower Similis-Pulchra	Aegiranum Maltby Vanderbeckei	Nuneaton Marine Band Maltby? Marine Band Seven Feet Marine Band	Productive Coal Measures	Middle Coal Measures
A	Modiolaris Communis Lenisulcata	Subcrenatum	Unconformity		Lower Coal Measures

generally 4 to 5 m thick, but thin to only 1.8 m in Ryton No.4 Borehole. In the north the beds include, at their base, the Vanderbeckei Marine Band (Mitchell, 1942). The contemporaneous shoreline extended from Meriden to Griff, south of Nuneaton, and to the south of this line the Marine Band horizon is represented by non-marine sediments (Fulton and Williams, 1989 p.192).

Thick Coal

Over this part of the Warwickshire Coalfield a number of coal seams combine to form the Thick Coal (Cope and Jones, 1970), the constituent seams of which are at some point either in contact, or separated by no more than a thin dirt parting. Farther south the seams separate again, and in the Binley area, where they have been worked, they are spread out over a considerable vertical interval. The aggregate thickness of coal at Binley, is even greater than in the true Thick Coal region, reaching over 10 m in Binley Colliery shafts. Mitchell (1942, p.8) considered that the Thick Coal comprised the Nine Feet (Slate), Ell, Ryder, Bare, Two Yard and Thin Rider Coals. Cope and Jones (1970, p.585) also included the Smithy (Lady) and High Main coals beneath the Nine Feet, but Fulton (1987, p.204) argued against inclusion of the Smithy in the Thick Coal.

The recent exploration has shown that the splitting of the Thick Coal into leaves approximating to its constituent parts is not simple (National Coal Board, 1985). For convenience a number of areas have been defined with distinctive seam sections; these are shown in (Figure 16). Fulton (1987) restricts usage of Thick Coal to the Prime Thick Coal.

The correlation of the constituent leaves of the Thick Coal throughout the district is difficult, but has been achieved with certainty using chemical variation and coal macerals. The parts which have been identified are in descending order Two Yard, Bare, Ryder, Ell, Nine Feet (which splits into two), High Main and Smithy. The Thin Rider Seam, which lies above the Two Yard Seam to the north, is combined with the Two Yard Seam forming a widely recognisable top zone within that seam.

On the western margin of the coalfield, in part of the zone of Partial Thick Coal (see Figure 16), the lower part of the Nine Feet, the High Main and Smithy seams are not developed; the western side of the Prime Thick Coal zone indicates where all the seams are closely associated. South-eastwards there is first a zone where many of the seams separate from each other; but the dirt partings within the major leaves are not more than 30 cm thick, though those between the major leaves are much more, (Splitting Thick Coal); next a narrow zone of Split Thick Coal where there are large intervals between all the leaves; then an area (Recombining Thick Coal) where the seams begin to come together again.

Thick Coal to Aegiranum Marine Band

The roof of the Thin Rider usually consists of black shale with ironstone bands. A fauna collected in Grinley's Mine [c.378 772] yielded *Anthracosia atra, A.* aff. *atra, A.* cf. *acutella*, and *Anthracosphaerium propinquum*. In Beddows Mine [3715 7712], the following fauna was found above the Thin Rider: *A.atra, A.simulans* and *Naiadites sp*. In Ryton No.3 Borehole, a similar fauna comprised *Anthraconaia cymbula, Anthracosia atra, A.* cf. *actuella* and *A.simulans*, together with fish remains including *Elonichthys* scales. The roof of the Two Yard at Newdigate Colliery yielded *Anthracosia atra* and a number of related species (Mitchell 1942). These faunas indicate a late Westphalian B, Lower Similis-Pulchra Chronozone age.

The interval between the Thin Rider and the Four Feet coals is generally about 15 to 20 m (Fulton and Williams, 1988 p.193), thinning south of Binley to 5-15 m. Above the black shale roof of the Thin Rider, the measures consist mainly of seatclays and shaly mudstones. In the Binley shafts, and in borings to the north, a thin coal (0.15 to 0.33 m) has been proved consistently about 10 m above the Thin Rider.

The Four Feet is impersistent; its roof commonly contains an *Anthracosia atra* fauna identical to that above the Thin Rider/Two Yard, and locally there is a marine band at this horizon, possibly the Maltby. The next coal upwards is the Half Yard, some 25 to 40 m above the Thick Coal. It occurs in a more arenaceous succession and has little or no associated fauna. The highest coal is thin and impersistent, lying 30-50 m above the Thick Coal. It marks the top of Westphalian B, and carries the Aegiranum Marine Band in its roof.

Westphalian C

Aegiranum Marine Band to Etruria Marl

The base of the Westphalian C stage is marked by the Aegiranum Marine Band which persists over most of the area. It passes into the Etruria Marl facies in the west between Meriden and Daw Mill, and Fulton and Williams (1988, pp.191-192) suggest that the relative topographical elevation here was fault-controlled.

The richest development of the Aegiranum Marine Band occurred in the Rouncil Lane Borehole, where the following diverse fauna was recovered; *Lingula mytilloides, Orbiculoidea* cf. *cincta, Dictyoclostus sp., Neochonetes granulifer, Plicochonetes waldschmidti, Tornquistia diminuta, Myalina sp.*, cf. *Pernopecten sp., Phestia sharmani, Euphemites anthracinus, Retispira sp., Hollinella* cf. *ulrichi, H.claycrossensis, Roundyella sp., Ditomopyge sp., Serpuloides stubblefieldi*, conulariid and fish debris. Such faunal associations are typical of nearshore environments, in contrast to the more offshore goniatite-dominated assemblages seen in some other regions at this horizon. In the Beddows Mine exploration drift [3731 7715] (Mitchell, 1942, p.11), the Aegiranum Marine Band yielded *Serpuloides?*, chonetoid fragment, *Lingula mytilloides, Orbiculoidea* cf. *nitida, Phestia acuta*, and conodonts including *Hindeodella sp.* and *Ozarkodina sp.* In Ryton No.3 Borehole, a fauna from the Aegiranum Marine Band from between 775.4 and 777.5 m, included *Hyperammina sp., L. mytilloides, L.* sp. nov., *Levipustula sp.* (fragmentary), *O.* cf. *nitida, Productus?* (fragmentary), *Dunbarella sp., Pernopecten carboniferous, Schizodus antiquus, Coleolus sp.* and an *Elonichthys* scale.

Above the dark grey mudstone of the Marine Band, the measures consist mainly of grey mudstones and seatearths, with some thin coals (rarely up to 0.3 m) and sandstones.

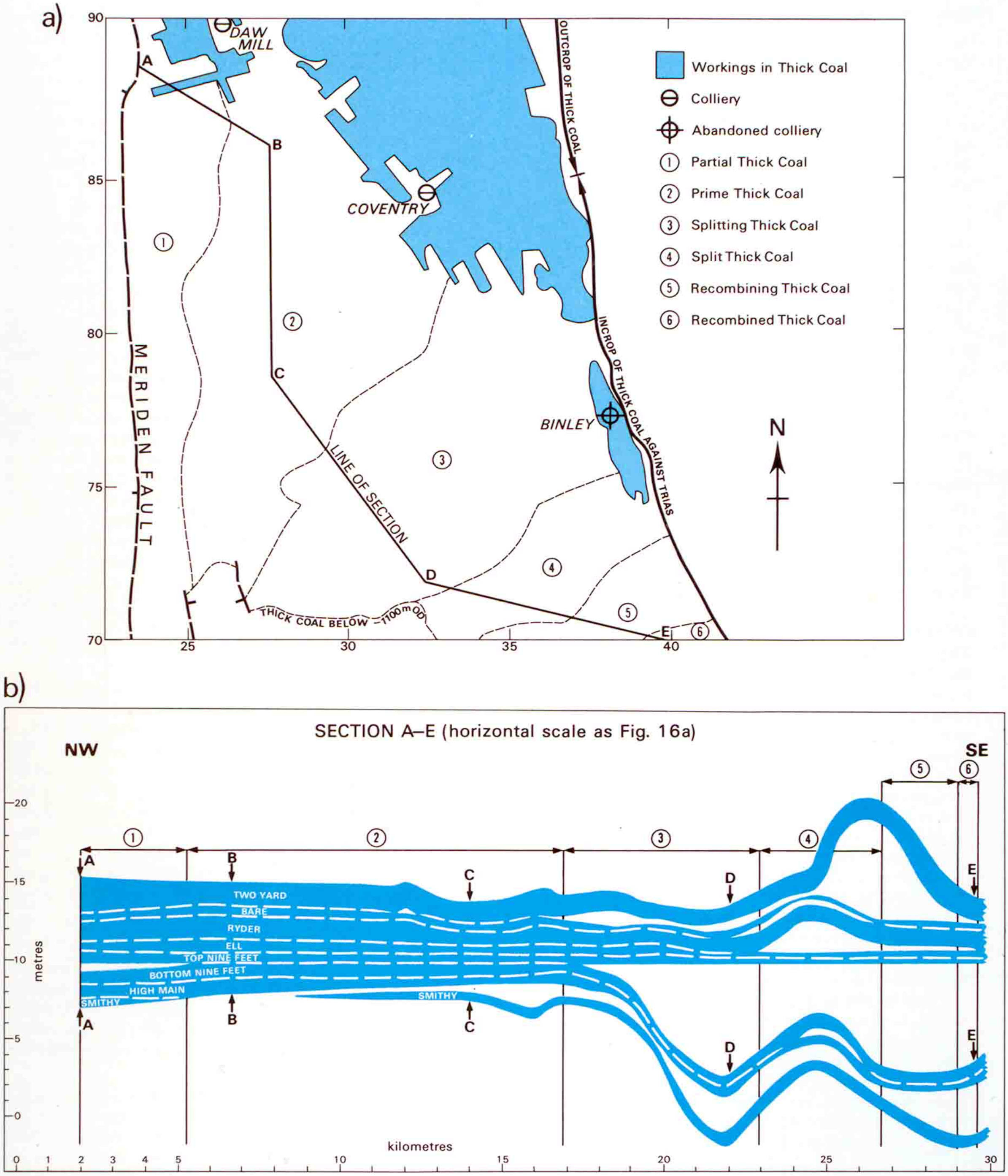


Figure 16a,b. Seam structure of Thick Coal (data from British Coal)

In Ryton No.3 Borehole, *?Euestheria* occurred in brown and dark grey mudstone, immediately above 0.03 m of coal about 34 m above the Aegiranum Marine Band.

Etruria Marl Formation

In the northern part of the Warwickshire coalfield the Etruria Marl consists of brown and red variegated 'marls' with lenticular beds of sandstone (Eastwood and others, 1923; Mitchell, 1942). In the Coventry area the formation is by comparison less distinctive. A sequence of mudstones, siltstones and sandstones, together with a few thin coals, mainly greyish in colour, but always variegated with red and brown, occurs between the grey Productive Coal Measures beds and the overlying Halesowen Formation; this is taken to be the Etruria Marl. The sandstones are commonly coarse and gritty, but the conglomeratic espleys, which characterise the Etruria Marl farther north are less common. The base of the Formation is diachronous reaching below the Aegiranum Marine Band in the north-west (Fulton and Williams, 1988 p.191). Its thickness varies from 30 to 160 m.

A description of the sedimentary facies of the Etruria Marl is given by Besly (1988, pp.203-204). He concludes that the beds were laid down in conditions transitional between those of a coal swamp delta and a well-drained alluvial plain.

Westphalian D

The precise ages of the Carboniferous formations above the Westphalian C are not firmly established but appear at least to be Westphalian D in part, though the upper beds may well be Stephanian. The Halesowen and Keele formations are here regarded as Westphalian.

Halesowen Formation

The Halesowen Formation varies from 60 to 125 m in thickness, and is dominated by thick beds of grey, coarse, feldspathic sandstone, interbedded with grey mudstones, siltstones, seatearths and rare coals. The Milton seam, near the base of the Formation, persists throughout much of the area, but the other coals are not widely developed. The sedimentary facies consists of lacustrine and coal-swamp components (Besly, 1988 p.210). A persistent bed of *Spirorbis* limestone, the Index Limestone, occurs north or Coventry some 35 m below the top of the Formation. Samples of the limestone from The Lawns [3450 9000], and from a depth of 532 to 536 m in the Birch Tree Farm Borehole, yielded fish debris and ostracods. Many of the boreholes penetrating the full thickness of the formation have cored only its lower part, and the top of the formation is imprecisely known. Cores of the entire Formation, recovered in the Birch Tree Farm Borehole, are held by the British Geological Survey. On a regional scale the Formation gradually oversteps the older Westphalian southwards and eventually rests on Lower Palaeozoic rocks (Old and others, 1987). Localised, sharper, unconformable contacts at the base of the Halesowen are visible on British Coal seismic lines around Fillongley and west of Kenilworth, but details of these have not been released.

Exploration drilling by British Coal has proved two coal seams the Milton and Broughton, which correlate respectively with the No.9, and Nos. 5 and 6 seams of the Withycombe Farm Borehole [4319 4017] near Banbury (Poole, 1978, p.15).

Keele Formation

The Keele Formation consists predominantly of 155 to 370 m of red-brown mudstones with subordinate, impersistent sandstones, and a few thin beds of *Spirorbis* limestone (Eastwood and others, 1923). Numerous calcretes occur in the mudstones, and the sandstones commonly include intraclast mudstone conglomerates. Extraclast conglomerates occur locally, and contain pebbles of Lower Palaeozoic sandstone, chert and limestone.

A description of the sedimentary facies of the Keele Formation is given by Besly (1988, p.211). He interprets the main sandstone units as alluvial channel deposits, and the mudstones and thinner sandstones as overbank deposits. The limestones apparently formed in flood-plain lakes, while the calcretes represent soil profiles.

At outcrop in the north-east, and in the few well documented shaft and borehole sections, there is a gradual passage from the predominantly grey lithologies of the Halesowen Formation to the mainly red-brown colour of the Keele Formation. A complete cored section of the Formation, from the Birch Tree Farm Borehole, is held by the British Geological Survey. In uncored boreholes the base of the Keele Formation is not as easily determined. A characteristic, widespread, very high gamma peak, recorded on geophysical logs, has been taken as marking the base of the Keele Formation in many British Coal borehole records, but the cores of the Birch Tree Farm Borehole proved that the gamma peak occurred 45 m below the colour change from red to grey. The top of the Formation is distinguished from the overlying Coventry Sandstone by its more argillaceous nature, and is rather indefinite in places.

Fossils are extremely rare in the Keele Formation. Fish debris, ostracods and the gastropod *Anthracopupa* occur in a limestone at Exhall [3414 8677]; Vernon (1912) recorded *Asterotheca (Pecopteris) arborescens, A. (P.) miltoni*, and *Acitheca (P.) polymorpha* near the top of the Formation at Longford Brickworks [349 842], and limestone at the same locality yielded *Carbonita fabulina, C. pungens* and *Anthracopupa* sp. (BGS collections). Besly (1988, p.210) reviewed the available fossil evidence, and concluded that the Keele Formation covers an age range from late Westphalian D to late Stephanian or possibly Autunian.

Westphalian D to Autunian: Enville Group

The Enville Group of the Warwickshire Coalfield was first defined as covering all the pre-Triassic strata that succeed the Keele Formation (Eastwood and others, 1923, p.77). This definition was modified by Shotton (1929, p.169) to include all the pre-Triassic rocks above the Tile Hill Beds of the earlier writers.

The outcrop of the Enville Group forms an inverted triangle with its apex at Warwick. It forms part of the southwards plunging syncline of the Warwickshire Coalfield, and the lithological units have outcrops convex slightly northwards. The subdivisions used in this account (Figure 3) are based on Old and others (1987).

The Enville Group comprises red and red-brown mudstones, siltstones and sandstones with subordinate breccias and conglomerates of similar sedimentary facies to the Keele Formation. Four formations (the Coventry Sandstone, Tile Hill Mudstone, Kenilworth Sandstone and Ashow formations) have been recognised at outcrop and in geophysical borehole logs: they have a total thickness of about 900 to 1100 m.

The occurrence in the Kenilworth Sandstone of the pelycosaurs *Sphenacodon brittanicus* and *Haptodus grandis* (Paton, 1974) and the amphibian *Dascyceps bucklandi* (Paton, 1975) lends support to the Permian age for the upper part of the Enville Group. All these species are confined to Autunian strata. A jaw-bone of the pelycosaur *Ophiacodon* discovered in the Coventry Sandstone '3/4 of a mile north-west of Coventry' (Murchison and Strickland, 1840, p.347) is assigned a late-Stephanian to early-Autunian age by Paton (1974). Less well attested are the views of Haubold and Serjeant (1973, p.908) and Haubold and Katzung (1975, p.118), based on scanty evidence from reptile footprints, that the base of the Permian should be placed at the base of the Enville Group.

There is no chronologically significant fossil evidence as to the age of the Enville Group below the Coventry Sandstone, but the general concensus is that it is uppermost Carboniferous (Westphalian D or Stephanian). Dix (1935) reviewed the floral evidence and placed the whole of the Enville Group in the Permian, but no significant plant fossils occur below the Tile Hill Mudstones. Three specimens of *'Strophalosia'* from the Enville Group figured by Howell (1859, p.32) have been reidentified as gymnosperm seeds *Cardiocarpon reniforme* and *C. ottonis* (Cox, 1953).

Provenance of the Enville Group

The provenance of the pebbles in the Enville Group is discussed by Shotton (1929, pp.190-198) who concludes that the majority were derived from the Precambrian and Lower Palaeozoic rocks of the Lickey Ridge to the west, (the only exception being those in the Corley Member). The assumption that the Lower Carboniferous pebbles, especially limestone, have a westerly source cannot be proved. These pebbles may equally probably have been derived from the northern end of the Warwickshire Coalfield.

Coventry Sandstone Formation

The Coventry Sandstone Formation spans the interval between the top of the Keele Formation and the base of the Tile Hill Mudstone Formation. It includes the conglomerate horizons of Arley/Exhall, Corley and Allesley (Eastwood and others, 1923, Shotton, 1929, Old and others, 1987). It is, however, misleading to name these units formally as conglomerates because they consist predominantly of sandstone with conglomerates occurring as lensing point bar and channel lag deposits. The Corley Member (Plate 6) is the only one to warrant formal naming and the other two have been relegated to unnamed sandstone units. The Coventry Sandstone is best defined as a predominantly arenaceous formation lying between two formations composed predominantly of mudstone, although locally it is argillaceous (Plates 4 and 5); this definition can be used in classifying geophysical logs of the exploratory boreholes. The formation is about 300 to 350 m thick in the south, increasing rapidly to around 550 m north of Coventry.

Excellent exposures in the lower part of the Formation, in the Websters, Hemming and Sons Ltd., Midland Brickworks [3423 8050], demonstrate the lateral impersistence of the sandstone units. Besly (1988, p 213) figures a section of this pit, and concludes that the beds represent "an alluvial sequence in which most of the discharge was concentrated in large flood events". Vernon (1912), and Eastwood and others (1923) both recorded *Walchia* here, an identification corrected to *Lebachia piniformis* by Florin (quoted in Wagner, 1983) who also recorded *L. frondosa* var. *zeilleri* and *Ernestiodendron filiciforme.*

The Midland Brickworks was notified in 1986 as a Site of Special Scientific Interest (SSSI), but unfortunately planning permission had already been granted for restoration. "Coventry City Council, as local planning authority, decided that the pressing local need for sports pitches and public open space outweighed the national importance of the SSSI and have decided to completely infill the pit" (Nature Conservancy Council, 1988, p 33).

Tile Hill Mudstone Formation

The stratigraphical limits of this formation have been given by Shotton (1929, pp.171-172). The Tile Hill Mudstone comprises the predominantly argillaceous sequence between the highest mappable persistent sandstone of the Coventry Sandstone and the predominantly arenaceous Kenilworth Sandstone Formation. It includes some impersistent sandstones, especially towards the middle of the sequence, and a thin channel lag conglomerate occurs at Beechwood. The thickness of the Formation varies from 250 to 300 m.

Good exposures of the mudstones are rare; they are red-brown, well bedded, locally silty and with green reduction spots. Sandstones are more significant than suggested by Shotton (1929). Several crop out in the south-western part of Coventry, though all die out rapidly along the strike. Some are of typical 'Enville' lithology: red, coarse, massive and fairly soft. Others, more characteristic of this formation, are hard, flaggy, red-brown or green, thin, fine-grained, calcareous, and interbedded with mudstone. There are numerous exposures of such sandstone, interbedded with mudstone and siltstone, in a stream between Wolfe Road, Canley [2900 7775] and Canley Ford [3127 7700].

Kenilworth Sandstone Formation

This formation, approximately 100 m thick, includes the 'Kenilworth Breccia Group' and the 'Gibbet Hill Group' as defined by Shotton (1929). The base of the former can be recognised only locally due to the impersistence of the breccia bands, which are channel lag deposits.

The base of the Kenilworth Sandstone is marked by the incoming of thick, massive sandstones forming a strong north-facing scarp from Hurst Farm though Gibbet Hill to Stoneleigh. West of Hurst Farm the scarp is broken by

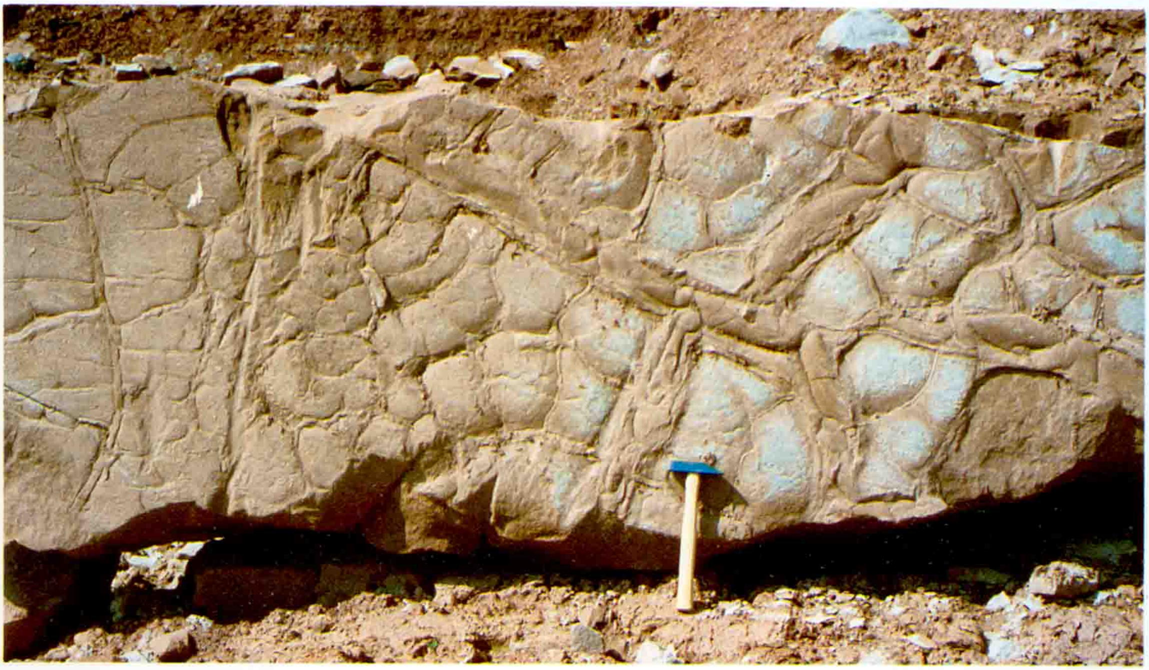


Plate 5 Base of sandstone block, showing cast of mud-cracks in underlying mudstone, Coventry Sandstone Formation. Websters, Hemming and Sons Ltd., Midland Brickworks [3423 8050]. MN27149.

Plate 6 Trough cross-bedded sandstone, Corley Member, Corley Rock [3040 8250]. A14543.

faulting, but the base of the Kenilworth Sandstone can be traced as far as the Warwick Fault. The top of the formation is taken at the onset of the thick mudstones of the Ashow Formation.

Red, massive, and commonly soft sandstones form the bulk of the formation with subordinate thin, lensing mudstones. Towards the base of the Formation the Gibbet Hill Conglomerate is locally present (Plate 7), and there are thin lenses of breccias mainly towards the top. There are few localities where any appreciable thickness of sandstone is exposed. In 1978, however, a pipe-trench was excavated across virtually the whole width of the Kenilworth Sandstone outcrop between Gibbet Hill [307 748] and Kingswood Farm [314 728]. This confirmed that most of the sandstones are rather soft, at least to depths of 2-3 m. A few very hard, flaggy, calcareous, lustre-mottled bands were encountered. Red-brown mudstones with green spots were also encountered, and varied from blocky to thinly bedded.

Ashow Formation

The Ashow Formation is equivalent to the Ashow Group of Shotton (1929), and comprises all the Enville Group above the Kenilworth Sandstone. It is predominantly argillaceous, but contains several thick sandstones. The total thickness of the formation is about 170 m.

The base of the formation is marked by the incoming of a sequence of mudstones 50 to 65 m thick, divided in places by a sandstone up to 15 m thick. These are the 'Whitemoor Marls' and 'Whitemoor Sandstone' named by Richardson and Fleet (1926, pp.297-298) after the former Whitemoor Brickworks, Kenilworth [297 717].

The major sandstone above these mudstones is about 60 m thick, and forms the long dip-slope on which Ashow is built. An almost complete traverse of the outcrop was provided by a trench west of Ashow. The sandstone is soft, flaggy, cross-laminated and deeply weathered, with a few hard calcareous bands.

TRIASSIC

Sherwood Sandstone Group

Kidderminster Formation

Rocks assigned to the Kidderminster Formation occurred in the Blyth Bridge Borehole [2119 8979] beneath the Bromsgrove Sandstone at 490.7 m, and were proved to the final depth of the borehole at 1068 m. There are no other provings, but the Formation probably occurs at depth over much of the area west of the Maxstoke Fault (Map 2).

Only a few short lengths of core were taken at Blyth Bridge, and these consist of mainly red-brown, commonly micaceous sandstone, with well rounded, 'millet-seed' sand grains. Many of the beds carry pebbles of quartz and quartzite, while others are crowded with red mudstone clasts. The pebble content increases with depth, and the chipping samples are interpreted as conglomerate between 1015 and 1048 m.

Bromsgrove Sandstone Formation

In the east and south of the area the Bromsgrove Sandstone rests upon pre-Triassic rocks with a marked unconformity. East of the Warwick Fault the Formation is between 25 and 35 m in thickness. Between the Warwick and Meriden faults it thickens to about 65 m, but remains the oldest Triassic formation. West of the Meriden and Maxstoke faults the Bromsgrove Sandstone thickens appreciably (Old and others, 1987) and is underlain by the Kidderminster Formation. The maximum proved thickness in this area is 180 m in the Blyth Bridge Borehole. The formation mainly comprises cross-bedded sandstones (Plate 8) with subordinate mudstones. The former are mostly buff or pale grey-green, generally well sorted, medium- to fine-grained and micaceous; they contain many erosion and lateral accretion surfaces. Intraformational conglomerates (with clasts of mudstone and siltstone) and mudstone-pellet beds are common in the lower part of the Formation. The mudstones are red-brown, and form mappable units west of Kenilworth and near Baginton, Bubbenhall and Whitley.

The formation exhibits cyclic sedimentation similar to the alluvial cycles described by Allen (1965), a complete cycle comprising locally pebbly sandstone, with an erosive base, passing upwards into mudstone (Figure 17). The major sandstones formed in migrating river channels. They are commonly cross-bedded, and some show slumping and distortion of foresets, dewatering structures, load casts and flame structures. The mudstones formed largely as overbank material deposited during floods. Such conditions of deposition accord with the lenticular form of individual sandstone and mudstone units.

Mercia Mudstone Group

The Mercia Mudstone Group consists predominantly of red-brown, blocky mudstones with minor green and laminated mudstones, and several thin siltstones and sandstones (Plate 3). The Blue Anchor Formation, at the top of the Mercia Mudstone, consists of 5 to 7 m of pale grey-green silty mudstones with thin siltstones and irregular dolomite concretions. It has a small outcrop in the south-east and occurs at depth beneath Jurassic rocks at Barston in the west.

The only other named subdivision is the Arden Sandstone which consists of up to 10 m of distinctive pale green-grey sandstone, siltstone and mudstone, sometimes interbedded with red mudstone.

In the east the Mercia Mudstone is about 180 m thick with the Arden Sandstone about 20 m below the base of the Blue Anchor Formation. West of the Warwick and Meriden Faults the Group has not been fully proved, but is probably at least 450 m thick, and with the Arden Sandstone over 100 m beneath the Blue Anchor Formation.

Penarth Group

A small outcrop of the Penarth Group occurs north of Princethorpe [398 720], and it is concealed beneath the Lower Lias at Barston [205 780]. At the base is the Westbury Formation consisting of about 8 m of dark grey, fissile mudstone yielding marine fossils. The overlying

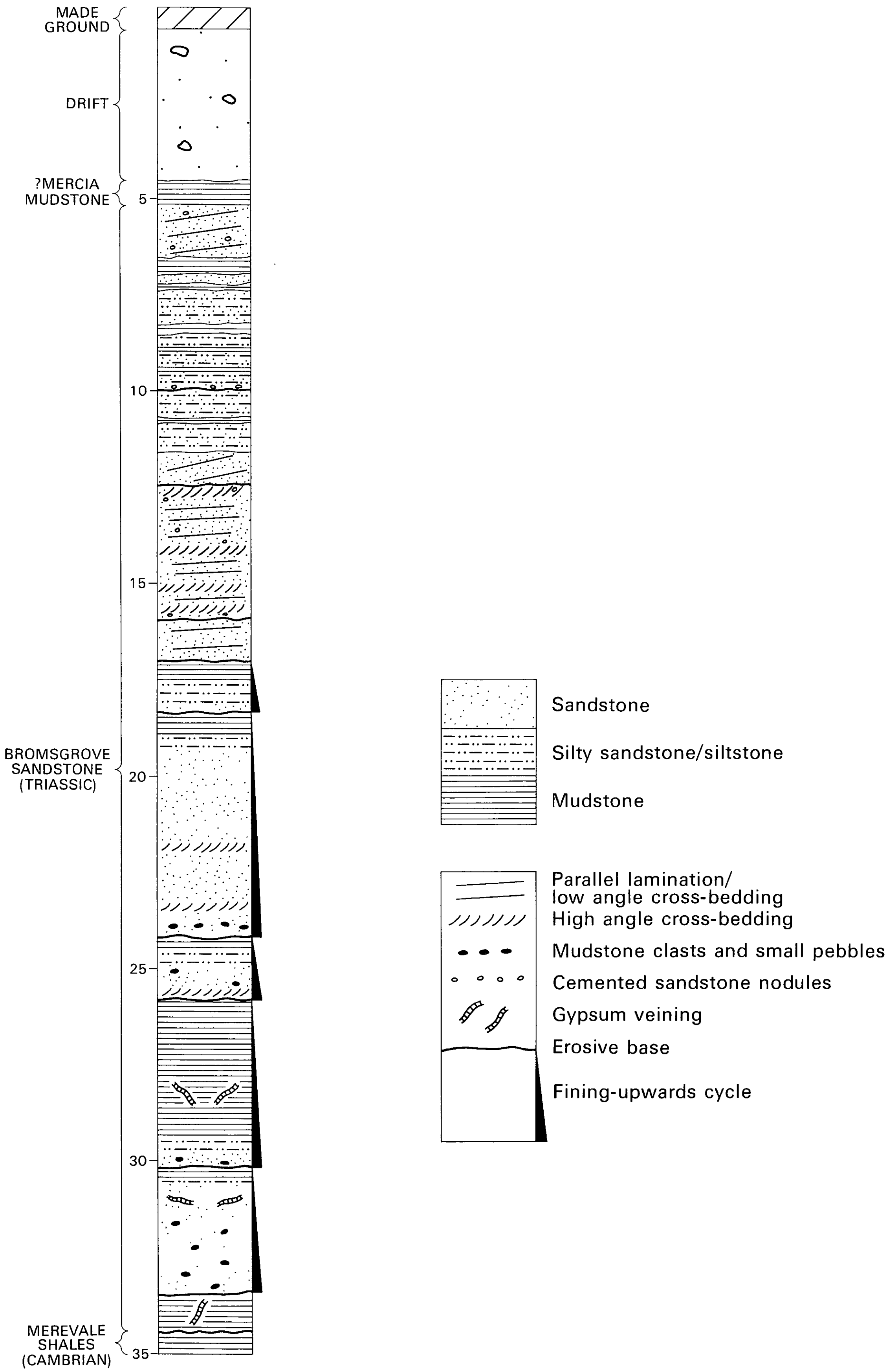


Figure 17. The Bromsgrove Sandstone in the Clifford Bridge Borehole

Plate 7 Interbedded conglomerate and sandstone, Gibbet Hill Conglomerate, Gibbet Hill Road [3046 7521]. A14559.

Plate 8 Cross-bedded sandstone, Bromsgrove Sandstone Formation, Bell Green Road, Coventry [3574 8217]. A14564.

Cotham Member consists of a similar thickness of grey-green and brown mudstone and siltstone, with a sparse marine fauna. The Langport Member, at the top of the Penarth Group, is pale grey, porcellanous limestone, up to 2 m thick near Princethorpe, but probably no more than 20 cm at Barston. A fuller account of the Penarth Group is given by Old and others (1987).

JURASSIC

Lower Lias

An outcrop of Lower Lias at Barston forms the eastern end of a faulted outlier lying mainly in the district to the west. Grey limestone and paper shale fragments occur in small pits south of Barston, and an estimated 15 m of beds are present. By comparison with the adjacent area (Old, 1982), the beds are of *Planorbis* or *Liasicus* Zone age, at the base of the Jurassic.

STRUCTURE

Pre-Carboniferous Structures

Little is known of the detailed structure of the Cambrian (including Tremadoc) basement, but broad structural units have been identified from faunal zones proved in a number of deep boreholes (Figure 13). These show folding along a NE-SW trend, with younger strata occurring to the south and west. This folding was probably the result of NW-SE Caledonian compression.

Pre-Triassic Structures

The overlying Carboniferous and Permian rocks lie in a shallow southwards-plunging syncline which constitutes the Warwickshire Coalfield. The form of the syncline at the level of the Two Yard Coal is shown in Maps 9 and 10, while the structures at the surface are shown in Figure 4 and Maps 1 and 2. Dips on the flanks are generally only 5 to 10° but steepen on the eastern and western limbs; overall, the syncline plunges south at 3 to 4°. Subsidiary folds superimposed on the main structure produce high dips locally; a series of tight N-S en-échelon folds is recorded in the Binley Colliery workings (Figure 15). Further north subsidiary folds have NNW-SSE or NNE-SSW trends (Figure 18).

Although the structures in all the Carboniferous and Permian rocks are broadly similar, in detail there are some important differences between the pre- and post-Halesowen rocks, as a comparison of Maps 1 and 2 with Maps 9 and 10 will show. The interpretation made by British Coal of their seismic data, shows that there was pre-Halesowen uplift on the Fillongley Anticline, and west of Kenilworth [25 72]; the Arley Fault may also have been active at this time.

These 'highs' are superimposed on the regional southwards and eastwards overstep by the Halesowen Formation on the older Westphalian rocks (Old and others, 1987). The Keresley Reverse Fault [31 83] could not be detected at the surface, and may also be a mainly pre-Halesowen structure.

Uplift initiated in late-Westphalian B times along the western margin of the Warwickshire Coalfield, possibly with an associated easterly downthrow on the Meriden Fault, resulted in facies changes in the Aegiranum Marine Band (Fulton and Williams, 1988) and in the Etruria Marl (Besly, 1988).

Post-Triassic Structures

An unconformable cover of Triassic and Jurassic rocks flanks the Palaeozoic inlier of the Warwickshire Coalfield. In the east, the Mesozoic rocks which overlap onto the Palaeozoic rocks, dip very gently southeast but are otherwise undeformed. In the west the limits of the Mesozoic rocks are sharply defined by the bounding growth faults of the Knowle Basin. The Triassic sediments thicken rapidly to the west of the Meriden, Maxstoke and Warwick faults. Although there is some evidence that they are gently folded, little is known about the structure of this area, due to the heavy drift cover. The sub-Triassic floor of the Knowle Basin has only been proved in the Dumble Farm Borehole [2306 8874], where Bromsgrove Sandstone rests on Coventry Sandstone. The deeper parts of the Basin include a considerable thickness of older Triassic rocks, while the underlying Palaeozoic may have been subjected to pre-Triassic inversion.

IGNEOUS ROCKS

Pre-Carboniferous Intrusions

Lamprophyre sills, up to 32 m thick, intrude the Cambrian rocks north of Meriden. Most of the sills show sharp, intrusive contacts with hornfelsed country rock.

The Priory Wood Borehole [2436 8258] encountered four lamprophyre sills between 541.4 m and 589.3 m, with only thin intervals of sedimentary rocks between; the thickest sill (31.7 m) lay between 548.9 m and 580.6 m. The highest sill was encountered only 11 m below the base of the Thick Coal, whereas there are, hereabouts, at least 35 m of Westphalian rocks in this interval before the Cambrian is reached. Because it is uncertain either that the baked mudstones overlying the highest sill are of Cambrian age, or that they are faulted against the Carboniferous mudstones just below the Thick Coal, the possibility that the sills are of post-Westphalian age cannot be entirely discounted. Thin sections described by Mr R K Harrison show that the sills consist of highly altered basic igneous rock, comparable to, but not identical with, the pre-Westphalian lamprophyres of the Nuneaton area (Taylor and Rushton, 1971). They are composed of a mesh of albite-oligoclase laths, with ferromagnesian minerals, entirely altered to chlorite, occurring as phenocrysts and interstitially. Pleochroic apatite is notable among the accessory minerals, together with quartz, biotite, leucoxene and iron oxide.

Mr R J Merriman reports that the alteration of these sills is much more intense, and of a different character, to that exhibited by a post-Westphalian sill in the Dale Wood Borehole (see Post-Westphalian Intrusions), so that the balance of the evidence is in favour of the sills at Priory Wood being pre-Westphalian in age.

Thin lamprophyre sills intrude the Cambrian rocks of the Woodcock Wood Borehole [2427 8682]. A 0.7 m sill below 665.6 m has irregular, lobate, crenulate and re-entrant contacts with the intruded sediments. There is a gradual coarsening of grain size, and the appearance of euhedral ferromagnesian phenocrysts, towards the centre of the sill. A second, 1.5 m sill below 667.1 m consists of

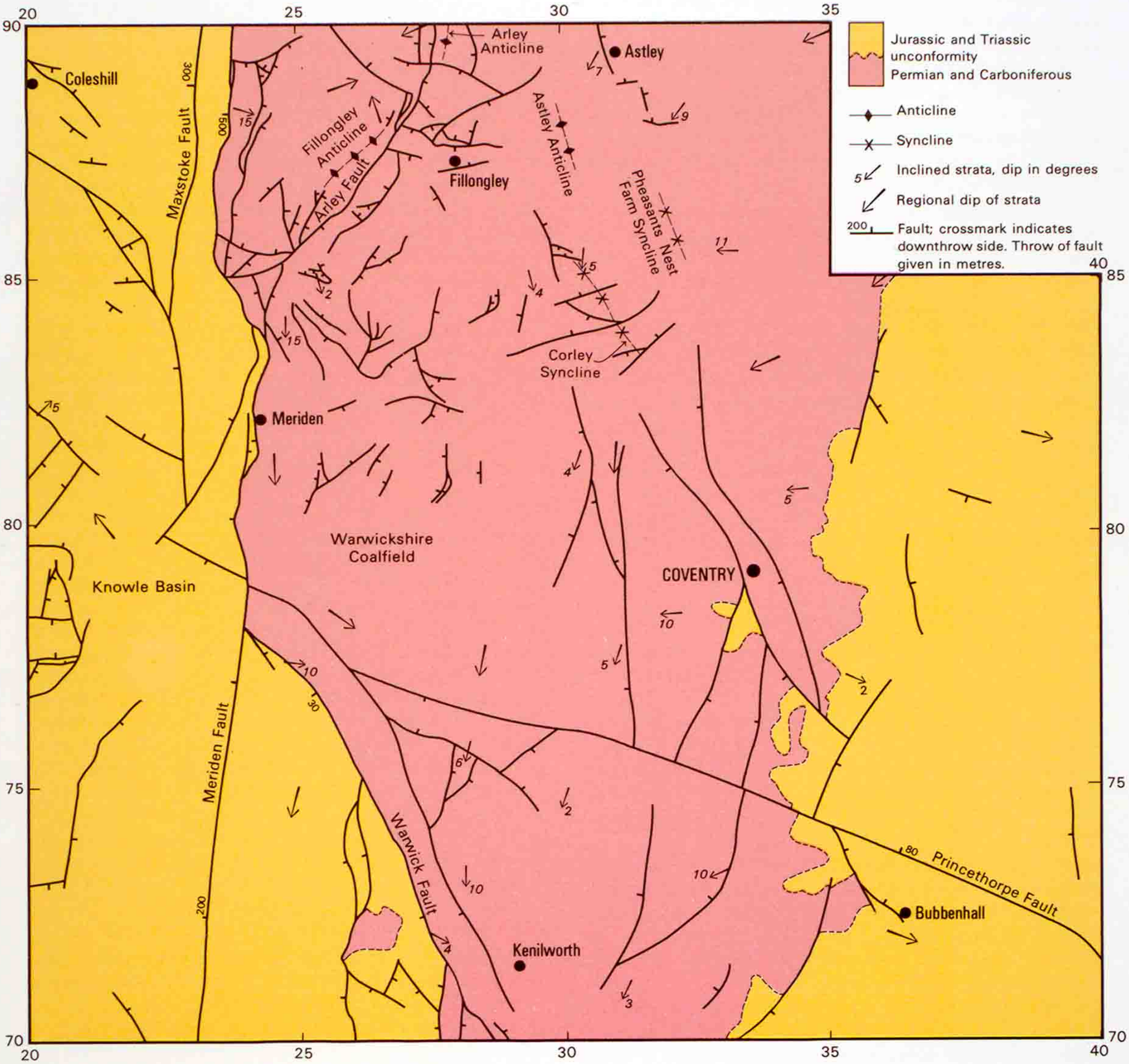


Figure 18. Principal structural elements of the study area

a complex of lamprophyre and sediment; the former occurs in discrete 'pillows' between 1 and 20 cm in diameter, and with lobate and crenulate, chilled margins. The pillows are not in contact with one another; a few have broken after solidifying and the broken surfaces are not chilled. The top 0.5 m of another sill occurs above the base of the borehole at 677.4 m, and has a concordant contact with the mudstone above. The mudstone between the sills is extensively hornfelsed with appreciable amounts of secondary pyrites and is contorted in some places. The cores of this sequence are held by the British Geological Survey.

The Hazel Grove [3015 8375] and Hollyfast [3004 8368] boreholes both encountered sills (0.5 m and 1.2 m thick respectively) cutting the Cambrian. The sill at Hazel Grove exhibits 'saw-tooth' contacts with the Cambrian mudstone, implying that the latter was lithified before intrusion occurred. In detail, however, the same contacts show slight lobate protrusions of igneous rock into mudstone, suggesting that lithification was incomplete.

Earlier workers (e.g. Hawkes in Taylor and Rushton, 1971, p.43) have suggested a Caledonian age for similar intrusions in the Nuneaton area. However, the features described above suggests that the sills at Woodcock Wood and Hazel Grove were intruded into poorly or incom-pletely consolidated sediments, and that they are, therefore, of late-Cambrian or earliest-Ordovician age.

Post-Westphalian A Intrusion

A 25.6 m thick dolerite sill is intruded between the Monks Park Shales and Productive Coal Measures in the Dale Wood Borehole [2632 8701]. The dolerite is mostly dark grey and fine to medium grained, though pegmatitic intervals and mudstone xenoliths occur within it. The rock has a poikilophytic texture of hornblende plates enclosing plagioclase laths and olivine pseudomorphs. Areas of intergranular texture, consisting of anhedral augite, plagioclase and Ti-magnetite also occur. Accessory minerals include apatite, late alkali amphibole, and biotite.

Secondary zeolite facies alteration of dolerite is pervasive: plagioclase is altered to albite; ferromagnesian minerals are replaced by chlorite or chlorite-saponite, magnetite is altered to leucoxene and zeolites are replaced by clay minerals and carbonates. Veins of chlorite, pyrite and carbonate are common.

The Westphalian mudstones above the sill are hornfelsed, proving a Westphalian A or younger age. This age is supported by the composition of the sill which is unlike that of the lamprophyre suite intruding the Cambrian near Nuneaton (Taylor and Rushton, 1971). By comparison with other Coal Measures intrusions in the Midlands (Kirton 1984) it is probable that the sill is no younger than Permian in age.

QUATERNARY

Glacial Deposits

All the older Quaternary deposits are the result of one period of glaciation, locally identified as the Wolstonian, and of the interglacial immediately preceding it. They are mainly of eastern or north-eastern provenance and, in the east, they include lithologies of eastern provenance which correlate with those of the type Wolston Series outcrop, which lies just to the east of this area (Shotton, 1953). The nomenclature and correlation of the deposits follows that of Sumbler (1983), which in turn is based on Rice (1968) and Shotton (1976). In the west and north, however, the flat-bedded, widely persistent outcrops of the type Wolstonian area are not as well developed, in part due to the uneven subdrift topography (Maps 5 and 6). Instead the boundaries of the lithological units are irregular and tend to interdigitate. In particular, there is an intermingling of the eastern Triassic-derived and chalky boulder clays which, in the east usually crop out separately (Old and others, 1987). In the south-west the glacial deposits appear to be of western provenance. In places, they interdigitate with the youngest eastern deposits and are presumed to be contemporaneous with them (Table 1).

The status of the Wolstonian glacial stage is uncertain, and is the cause of much debate. Shotton (1989) maintains his earlier view (Shotton and West, 1969) that the Wolstonian Stage post-dates the Anglian Stage. However, Sumbler (1983) tentatively regarded the Wolston Series as Anglian in age, a view supported by Old and others (1987), Rose (1989) and by the present writers. Fossiliferous silts, in a channel at the base of the Baginton Sand and Gravel at Waverley Wood Quarry [364 714], contain molluscs which yield an isoleucine epimerization age of about 600 000 BP (Bowen and others, 1989), i.e. they pre-date the Anglian. Shotton (1989) concludes that there is a "considerable unconformity" between the silts and the overlying gravel of the Baginton Sand and Gravel, but, in the view of the present writers, this unconformity is of the type commonly found in fluvial channels, and does not represent a major time span. Striking similarities between the floras and faunas from these silts, and similar silts from within the Baginton Sand and Gravel at the nearby Brandon Wood pit [383 763] (Gibbard and Peglar, 1989; Coope, 1989), suggest that the deposits are contemporaneous. There is no dispute that the glacial deposits of the Wolston Series immediately post-date the Baginton Sand and Gravel, and the conclusion drawn here is that they are, therefore, Anglian in age.

Baginton Sand and Gravel

The oldest Quaternary deposit known with certainty is the Baginton Sand and Gravel which crops out widely on both sides of the Avon, especially at Baginton and up-river from Bubbenhall. From Coventry to Kenilworth there are several elongated outliers of sand and gravel which have also been assigned to this unit. The term has been introduced to include both the Baginton-Lillington Gravel and the Baginton Sand of Shotton (1953) for, although sands normally overlie and overstep gravels within the deposit (Plate 1), in many places there is no mappable boundary between the two lithologies. The maximum thickness between Bubbenhall and Ryton-on-Dunsmore is about 10 m, the gravel and the sand each being some 5 m thick.

The gravel is of two types (Shotton, 1953, p.214-216). The 'Baginton facies' is dominant and consists almost entirely (up to 98 per cent) of well rounded pebbles of quartzite and quartz (hereafter, Bunter pebbles or quartzites), presumably derived from the Triassic 'Bunter' Pebble Beds (Kidderminster Formation), with a little locally derived Triassic material, particularly near the base. Coal is locally abundant on foresets. The outliers between Baginton and Kenilworth also contain a little flint. The 'Lillington facies' occurs mainly south of the area, but forms part of the deposit at Waverley Wood. 'Bunter' pebbles are again predominant, but are accompanied by Jurassic limestones, ironstones and robust fossils. The Jurassic material probably came from the Cotswolds, and the 'Bunter' pebbles and coal ultimately from the West Midlands, although the clasts may have been reworked from Tertiary or older Quaternary deposits of which no evidence remains. The fauna and flora of these deposits, described by Kelly (1968), Osborne and Shotton (1968), Old and others (1987), Coope (1989), Gibbard and Peglar (1989), and Shotton (1989), demonstrate that a change from a boreal to a cold climate took place during their deposition.

The overlying sand is generally fine- to medium-grained, and is clean and well sorted, with many lenses of 'Bunter' pebbles and coal fragments, particularly in concentrations along the foresets. Current directions, as indicated by the foresets, are variable. In the pits at Bubbenhall and Ryton-on-Dunsmore they mostly suggest a flow from between west and south.

Thrussington Till

The Thrussington Till, generally 3 to 5 m thick, overlies and overlaps the Baginton Sand and Gravel. Its basal contact is generally flat or gently undulating and sharp, suggesting that the underlying sand was frozen when the till was deposited.

The contact with the overlying Lower Wolston Clay is gradational, and there is an upward transition, through about 1 m, from red stony till to grey-brown, largely stoneless clay.

The Trias-rich variant of the Thrussington Till is dominant. It is a tough red-brown clay, containing pebbles and blocks mostly of green-grey Triassic sandstone and siltstone, with some of red mudstone and Carboniferous sandstone, many Bunter pebbles and small fragments of coal. Rarer erratics include Leicestershire granodiorites, Coal Measures ironstones and Lower Carboniferous limestones. Near Walsgrave the typical till is interleaved with a brown till containing chalk and flints.

Boulder clay closely resembling Thrussington Till characterises many of the outcrops in the Wroxall area. In places, it lies at the base of the glacial sequence, whilst in others it lies between lake deposits and sand and gravel. It also forms much of the boulder clay plateau hereabouts where commonly it is closely associated with flinty and chalky boulder clay. In boreholes, it is usual for chalky boulder clay to overlie non-chalky till (Cannell and Crofts, 1984). A few boreholes have proved glacial lake deposits and sand and gravel within the boulder clay (Cannell 1982, pp.43, 48), in contrast to the situation further east where the Thrussington Till forms a single bed overlying the Baginton Sand and Gravel.

The flint- and chalk-free boulder clay of the Wroxall area was included by Tomlinson (1935, fig. 1) with the 'Western Drift'. Shotton (1968a, p.58), however, found no western erratics in the boulder clay between Oldwich House and Frogmore Wood, and concluded that it was of northerly derivation. During the present survey, many angular, grey, quartzite erratics were found between Clattyland Wood and Honiley. These are comparable with the Lickey and Hartshill quartzites, which crop out respectively to the west and north-east, and so do not show the direction of derivation of the till.

The boulder clay varies rapidly in thickness, particularly where it fills sub-drift valleys. An exceptional thickness of 18 m was proved in a borehole at Hay Wood [2063 7082], but boreholes nearby proved only a few metres of boulder clay (Cannell and Crofts, 1984).

Wolston Clay and Glacial Lake Deposits

The Wolston Clay is present in the main area of glacial drift in the east, and may be represented by similar clay in several of the outliers. In many places it comprises lower and upper divisions separated by the Wolston Sand and Gravel.

The dominant lithology is an almost stoneless clay or silty clay, grey-brown to chocolate brown when fresh, but weathering to reddish brown; it is usually calcareous, particularly in the upper part, and commonly contains small calcareous 'race' nodules in the weathered zone. The Wolston Clay, though at first sight massive and structureless, is generally finely laminated, and lenticles of pale brown silt and sand occur, especially just below the Wolston Sand and Gravel. These laminated beds indicate deposition in standing water.

The Wolston Clay is rarely completely free of stones, and usually contains scattered pebbles interpreted by Shotton (1953, p.223) as drop-stones from icebergs melting in a glacially impounded lake. The most common pebbles in its lower part are of Bunter quartzite and Triassic sandstone and siltstone (as in the Thrussington Till). Chalk, flint and Jurassic limestone are commoner in its upper part marking the arrival in the area of the Oadby Till ice-sheet. Larger erratics, many polished and striated, including Leicestershire granodiorites, Jurassic limestone, and Carboniferous limestone and sandstone are common over the outcrop. Bodies of stony till occur locally within the Wolston Clay, particularly in its upper part. Some of the tills are red and mainly of Triassic material; others are brown or grey and derived from Chalk and Jurassic rocks; the two types resemble the Thrussington and Oadby Till respectively.

The glacial lake deposits in the west are mainly red-brown, laminated clays and silts with minor bands of sand. Laminations are not strongly developed everywhere and some of the deposits grade into red, Triassic till. The deposits are commonly interbedded with thicker accumulations of sand and gravel and boulder clay, and all show rapid variations in thickness which are compounded by the fact that the deposits were laid down upon an uneven sub-drift topography. Their maximum recorded thickness of 15.6 m, proved in a borehole near Frogmore Farm [2363 7535], included 2.6 m of sand and gravel (Cannell, 1982 p.46).

Wolston Sand and Gravel

The Wolston Clay in the east is divided into lower and upper parts by the Wolston Sand and Gravel. The typical lithology is fine- to medium-grained red sand and silt, commonly containing layers of plastic clay and silty clay. A basal pebbly layer is present in many places, and generally contains Bunter quartzite, green-grey Triassic sandstone and siltstone and rolled pellets of Wolston Clay. Jurassic and Cretaceous clasts are rare, and presumably most of the material was derived from the Trias-rich ice which deposited the Thrussington Till.

Sand and Gravel (undivided)

In the west sand and gravel is interbedded with the other glacial deposits and forms the bulk of the deposits infilling the Blythe Valley (Plate 2; Figure A 18). It occurs at all levels within the sequence but mostly pre-dates the youngest boulder clay of the Wroxall plateau. The clasts are almost exclusively of 'Bunter' quartzite and quartz, with rare sandstone and mudstone. Between Coleshill and Packington Lane Farm the lower part of the sand and gravel contains appreciable quantities of angular flint.

As the glacial deposits are traced westwards towards the Blythe Valley, sand and gravel becomes dominant in the sequence, emerging from beneath till and is contiguous with, and therefore presumably contemporaneous with, deposits laid down within the valley.

Oadby Till

The Oadby Till consists of grey clay, weathering brown, with abundant pebbles and boulders of chalk, flint and Jurassic limestone and sandstone, and rarer ones of Bunter quartzite, Triassic sandstone, siltstone and mudstone, Carboniferous sandstone and coal. The clay matrix was largely derived from Jurassic mudstones, and transport was from between NNE and east. The main outcrop within the present district occurs near Barnacle where Oadby Till caps Wolston Sand and Gravel. Chalky boulder clay of similar lithology occurs sporadically throughout the area, but does not occur as part of a clearly defined stratigraphic sequence.

Dunsmore Gravel

The Dunsmore Gravel, commonly 3-4 m thick and rarely over 6 m, caps a plateau between Ryton Heath Farm and Burnthurst Farm. Other outliers assigned to it occur between Binley Woods and Pinley in south-east Coventry.

It consists of brown, commonly ochreous, poorly sorted, sandy and clayey gravel containing lenses of sand, and is generally particularly clayey in its lower part. The surface layers are especially gravelly, possibly as a result of frost action. The pebbles are mostly of flint (in places up to 50 per cent), Bunter quartzite, Carboniferous sandstone and Jurassic ironstone, with some of Triassic sandstone. Where unweathered, the gravel also includes Jurassic limestone and chalk. Invariably the upper layers are leached and decalcified, with a layer of iron-pan 0.3 m to 0.6 m below the ground; in places a hard 'motherstone' has formed, consisting of gravel strongly cemented by limonite.

Fluvio-glacial Sand and Gravel

Fluvio-glacial sand and gravel occurs along the eastern side of the River Blythe, overlapping the margins of the underlying glacial sand and gravel. It consists of poorly sorted, commonly clayey sand and gravel, enclosing bodies of till-like clays. The pebble content resembles that of the glacial gravels, with Bunter quartzite pebbles predominant, but also including a small proportion of (Welsh?) Lower Palaeozoic rocks. The clays are dominantly red-brown, and contain Bunter quartzite pebbles and fragments of locally derived sandstones, and a little coal.

River Terrace Deposits

Fluviatile deposits form substantial spreads in the valleys of the Avon, Sowe and Blythe. All post-date the suite of glacial and fluvio-glacial deposits and are broadly similar in lithology, being composed of gravelly sand with lenses of silt. The pebbles in the Avon and Sowe terraces are mainly Bunter quartzites and flints, while those found in the Blythe Terraces are almost exclusively Bunter quartzite.

Most of the deposits are preserved as flat-topped terraces, and the terrace-flats have been classified according to their levels above the present alluvium. There are four main levels, though there are some deposits that are higher than the highest terrace-flat. The 1st Terrace of the Avon is about 1.5 m above the alluvium near Rugby. The main flat (2 or 2a) of the 2nd Terrace is about 5 m above the alluvium. Below the confluence of the Avon and Sowe, contiguous deposits rise locally to a less definite flat (2b) slightly higher than the main terrace. The higher terrace-flats are more fragmentary. A few small shelves between the 2nd and 4th terraces have been tentatively assigned to the 3rd Terrace, but there are too few of these to be certain that all lie on the same thalweg. The 4th Terrace lies 15 m above the alluvium. Terraces occur at only two levels in the Blythe Valley: the 1st Terrace rises to about 2 m above the alluvium, and the 2nd Terrace a further 2 m.

Based on evidence from the lower Avon to the south-west of the area, the 4th Terrace deposits are known to be the oldest, dating from an undefined interglacial between the Hoxnian and Ipswichian stages (Bridgeland, Keen and Maddy, 1989). The 3rd Terrace is assigned to the Ipswichian interglacial on the basis of faunas from the lower Avon (Tomlinson, 1925), and the occurrence of *Hippopotamus* in 3rd Terrace gravels in the Sherbourne Valley, Coventry [323 791] (Shotton, 1929). Cold climate mammalian faunas occur in the 2nd Terrace deposits downstream from the district (Tomlinson, 1925), and possibly also at Little Lawford [464 773]: they are dominated by *Mammuthus primigenius* and *Coelodonta antiquitatis*. Extensive subartic insect faunas occur in the 2nd Terrace near Brandon [390 754] and near Evesham, and associated peats have yielded mid-Devensian radiocarbon dates of about 30 000 and 38 000 BP respectively (Coope, 1968; 1962). No fauna is known from the 1st Terrace deposits, but these are presumably late-Devensian to early Flandrian in age.

Alluvium

Alluvial deposits occur in all but the smallest valleys. Their composition reflects local sources, both solid and drift, and even in the largest valleys they rarely exceed 6 m in thickness. The deposits are commonly divided into an upper bed of clay and silt, with scattered pebbles, underlain by sand and gravel.

APPENDIX II

GEOTECHNICAL DATA FOR THE STUDY AREA

INDEX TESTS

Atterberg Limit data:

Liquid limit (LL), plastic limit (PL) and plasticity index (PI) defined as PI= LL – PL are shown in the form of Casagrande diagrams with Unified Soil Classification System (USCS) codes (Carter, 1983) in Figures 9a, 9b, 9c, 19a, 19d, 20a, 20b and 20c. Variation of liquidity index (LI) defined as LI = (moisture content – PL)/(LL – PL) is shown with depth in Figures 21(a-d), 22b and 22d, and with cohesion in Figures 22a, 22c and 23(a-d).

Keele Formation

The Keele Formation consists of a succession of red-brown mudstones and sandstones, outcropping largely in the north-east part of the study area. Plasticity relationships are shown in Figure 20c and liquidity index v depth in Figure 21d. These reveal a USCS soil classification (Carter, 1983) of CL and CI (low and intermediate plasticity) with most samples falling well above the A-line, and an inverse LI v depth correlation similar to that for Mercia Mudstone. The range of natural moisture contents for the Keele Formation is narrow (8% to 21%).

Enville Group

The Enville Group represented, in descending order, by the Ashow, Kenilworth Sandstone, Tile Hill Mudstone and Coventry Sandstone formations, consists of interbedded red-brown mudstones, sandstones and siltstones, with some conglomerates. Casagrande plasticity charts for the Ashow Formation and Kenilworth Sandstone are shown in Figures 20a and 20b. Most of these data are from shallow samples (< 3 m) and the degree of weathering is probably high. Ashow Formation clays/mudstones generally belong to weathering zone III. Liquid limits for the clays and mudstones are occasionally high (LL >50%), placing them in group CH of the USCS classification (Carter, 1983). Particle size data for the low plasticity Ashow Formation and Kenilworth Sandstone mudstones is apparently dominated by silt (between 30% and 80%). No plasticity data are available for the Tile Hill Mudstone, but the indications are that index properties for the cohesive components of all the Enville Group members are very similar. It is unfortunate that few data were obtained for the Tile Hill Mudstone, a relatively widespread unit in the central part of the study area.

Plasticity and density/moisture content diagrams for the Coventry Sandstone are shown in Figures 19a-19c. The majority of samples fall within plasticity groups CL and CI on the USCS classification (Carter, 1983) with a small number exceeding a liquid limit of 50%. On the plasticity chart (Figure 19a) the points are concentrated 'higher' above the A-line than is the case for the Mercia Mudstone. This may reflect mineralogical differences and suggests a greater degree of homogeneity in the case of the Coventry Sandstone data. The equation of the linear regression 'T-line' is PI = 0.72 (LL – 11.2) and has a correlation coefficient, r = 0.95. Data from discrete boreholes show a decreasing trend in liquidity index with depth, but taking the data as a whole the correlation is poor (Figure 22d). Moisture content, liquid limit and plastic limit data, and derived parameters, for the Coventry Sandstone as a whole show an excellent gaussian (normal) distribution; the arithmetic mean values for moisture content, liquid limit and plastic limit being 16%, 35% and 18% respectively (Table 4). Liquid limits for the Coventry Sandstone and Mercia Mudstone are very similar, though the plastic limits for the former are on average 2% lower. Particle size data encompass the range from 43% clay size to 94% sand size.

Sherwood Sandstone Group

This group is represented in the data base by a few records from the Bromsgrove Sandstone Formation, which forms the upper part of the group (above the Kidderminster Formation). The lithologies range from brown-green, dense sand and sandstone, to red-brown mudstone often described as 'marly', the index properties of which resemble those of the Mercia Mudstone clays. Liquid and plastic limits have arithmetic means of 31% and 17% respectively. The dense sands are generally of medium sand size, with variable silt contents up to 30%.

Mercia Mudstone Group

The Mercia Mudstone consists of a series of red-brown, heavily overconsolidated clays or mudrocks with bands of sandstone or siltstone. The Mercia Mudstone (undivided) falls largely into the CL and CI classes, i.e. clays of low to intermediate plasticity. Some silts are present which plot below the A-Line (Figures 19d & 19e). The equation of the linear regression 'T-line' is PI = 0.72 (LL – 14) having a correlation coefficient r = 0.86. The arithmetic mean liquid and plastic limits for the Mercia Mudstone are 35% and 20% respectively, and a good Gaussian (normal) distribution of values is found. The values of LL and PL are low for a clay having a clay fraction as high as 60%, but this is attributed to aggregation of clay particles into peds cemented by silica (Sherwood and Hollis, 1966; Dumbleton, 1965; Chandler and others, 1968). Unfortunately, very few particle-size analyses were found for Mercia Mudstone clays in the study area, hence no values of clay activity (Ac = PI /%clay) can be given. Other sources (e.g. Chandler and others, 1968), point to low values in the range 0.25 to 1.1 (i.e. largely inactive). However, it should be pointed out that many particle size analyses are suspect because of ineffective disaggregation prior to testing. Also the liquid limit as specified by British Standards has proved inconsistent, again due to partial breakdown of aggregations during test preparation (Sherwood and Hollis, 1966).

The inverse correlation between dry density and moisture content is shown in Figure 19f, with broad moisture content groupings for 'weathered' and 'unweathered' taken from Cripps and Taylor (1981). The boundary between zones III and IV, suggested by Chandler (1969) at LL = 38%, does not appear to apply to the data. These groupings are also shown on the Casagrande plot (Figure 19d). Liquidity indices vary widely (from +1 to –1), and there is a general decrease in liquidity index with depth (recorded to 18 m). An increase in liquidity index with increasing weathering is to be anticipated, but weathering

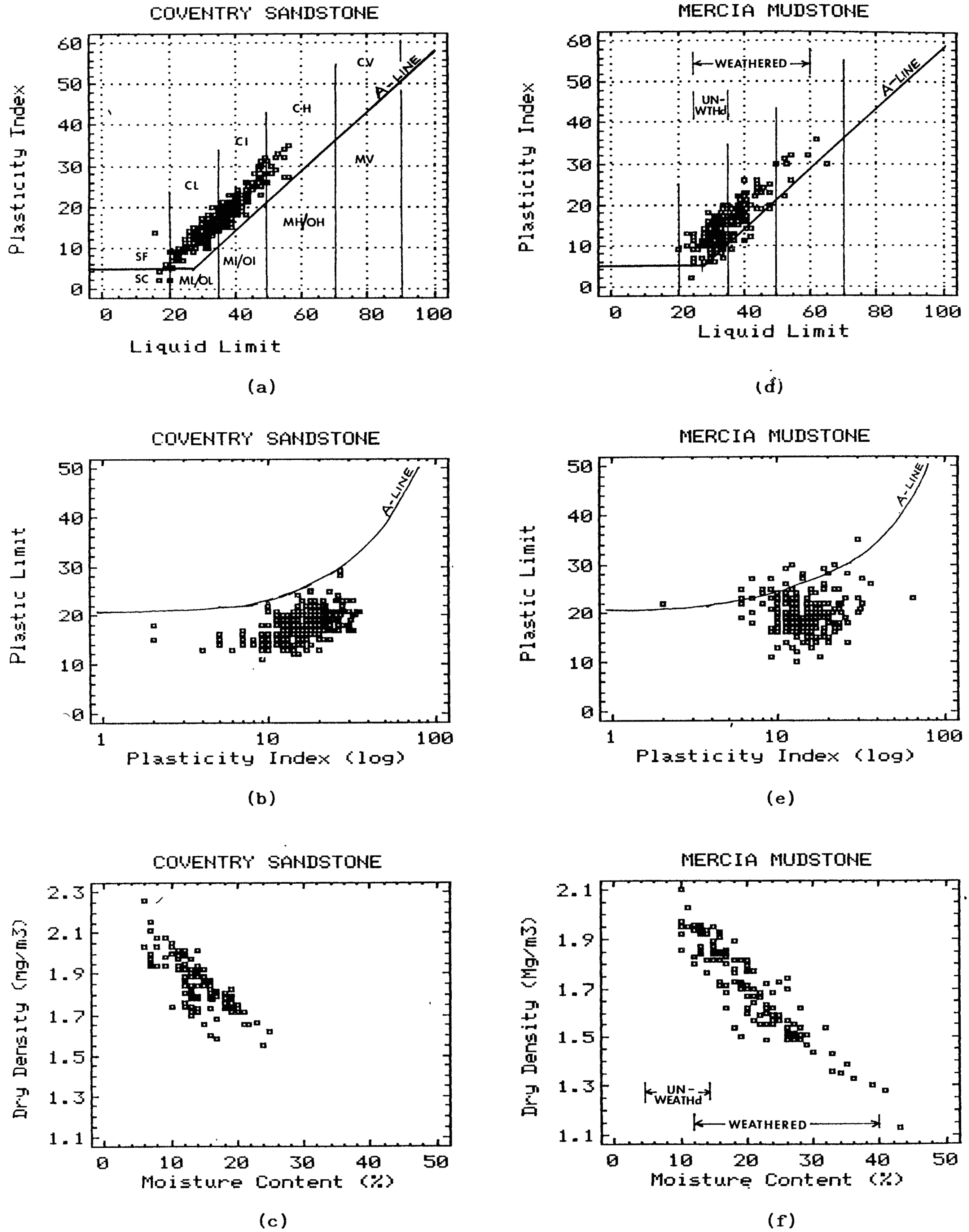
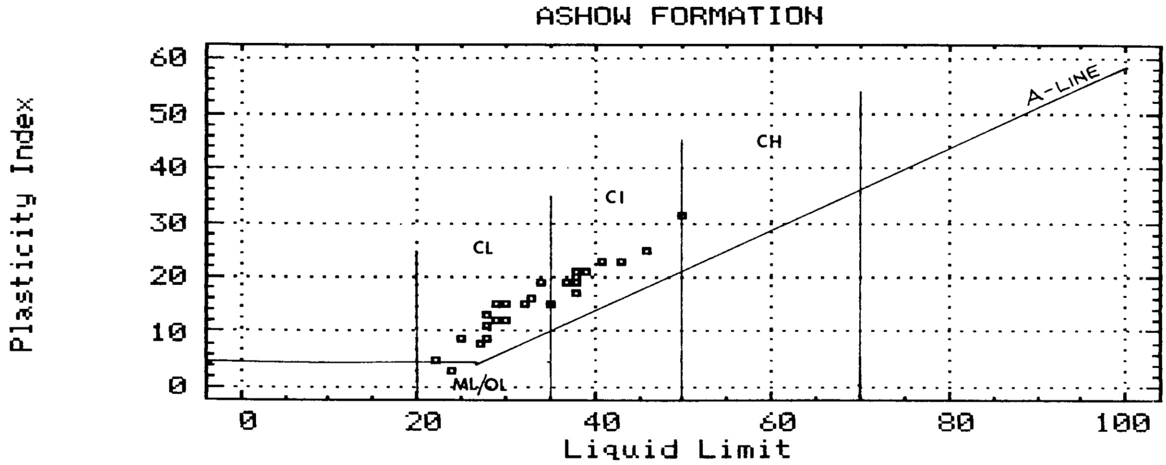
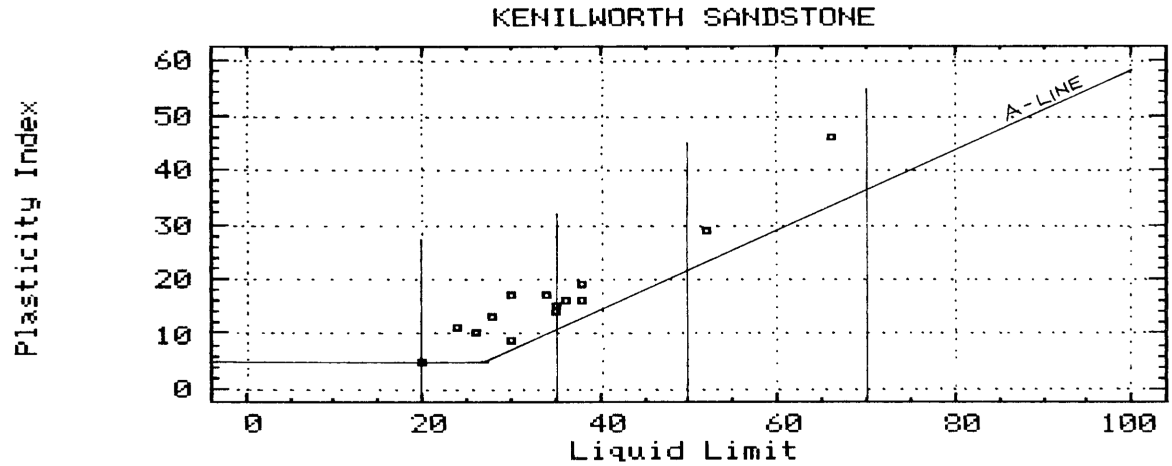


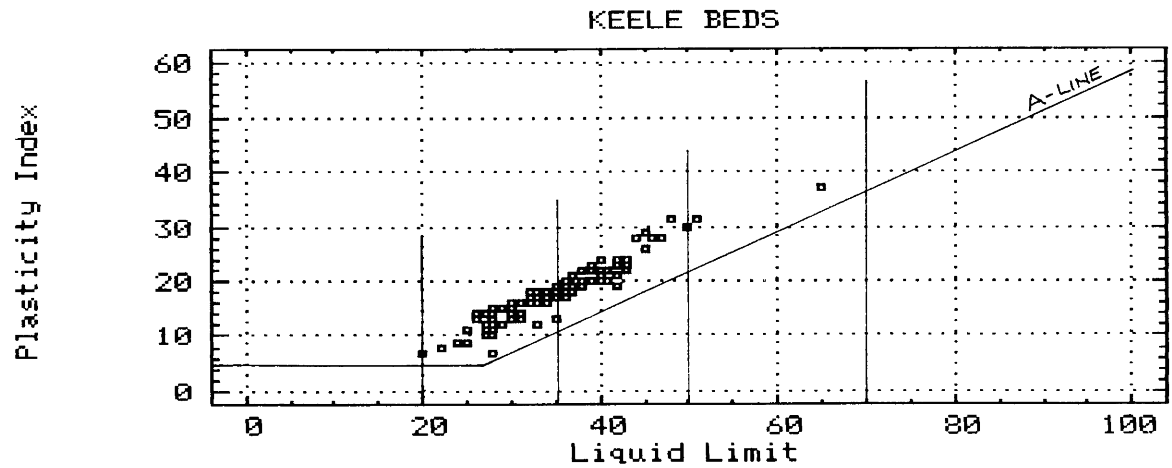
Figure 19a,d Plasticity index vs Liquid limit for Coventry Sandstone and Mercia Mudstone. **b,e** Plasticity limit vs Plasticity index for Coventry Sandstone and Mercia Mudstone. **c,f** Dry density vs Moisture content for Coventry Sandstone and Mercia Mudstone



(a)



(b)



(c)

Figure 20a-c Plasticity index vs Liquid limit for Ashow Formation, Kenilworth Sandstone and Keele Formation

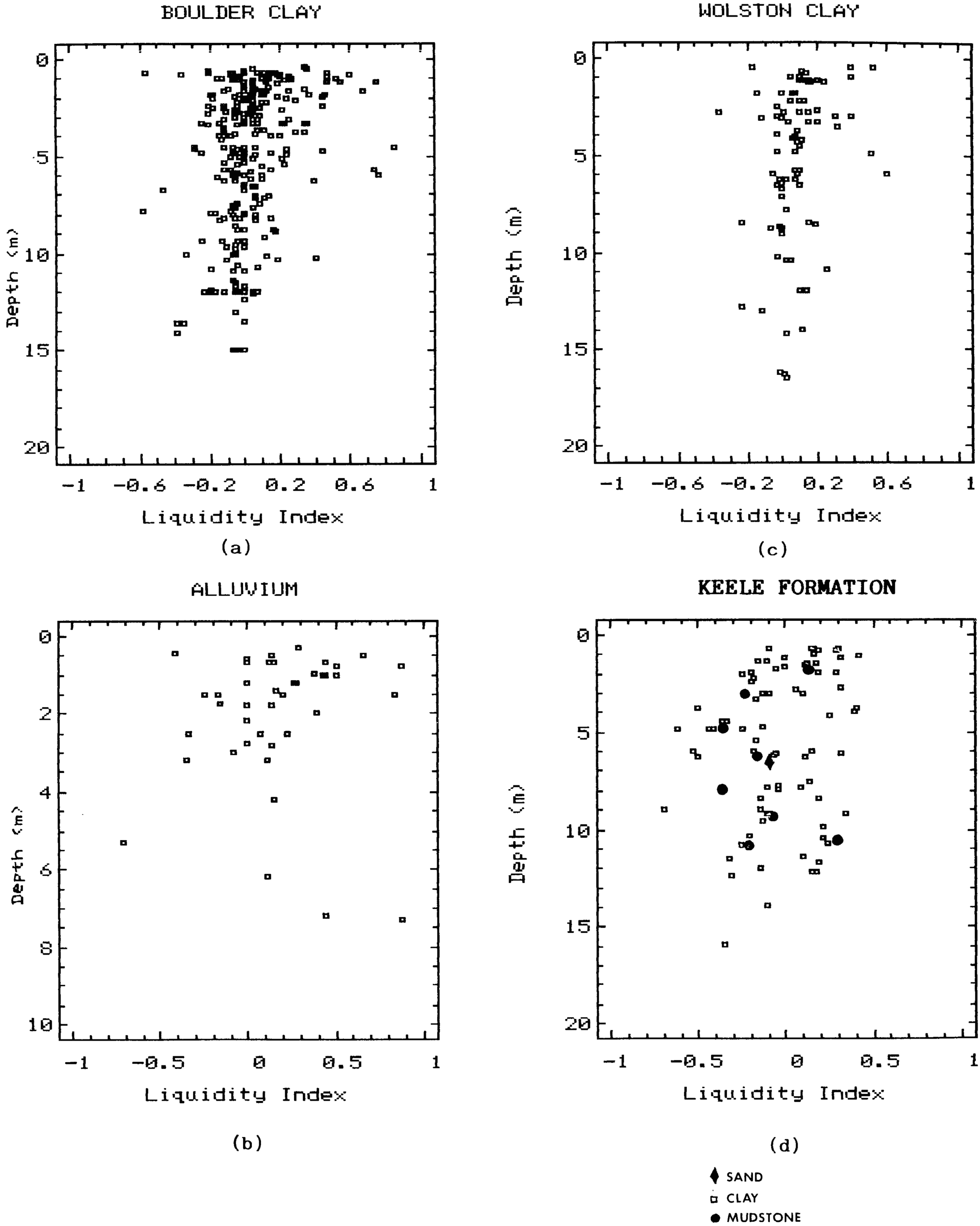


Figure 21a-d Depth vs Liquidity index for Boulder Clay, Alluvium, Wolston Clay and Keele Formation

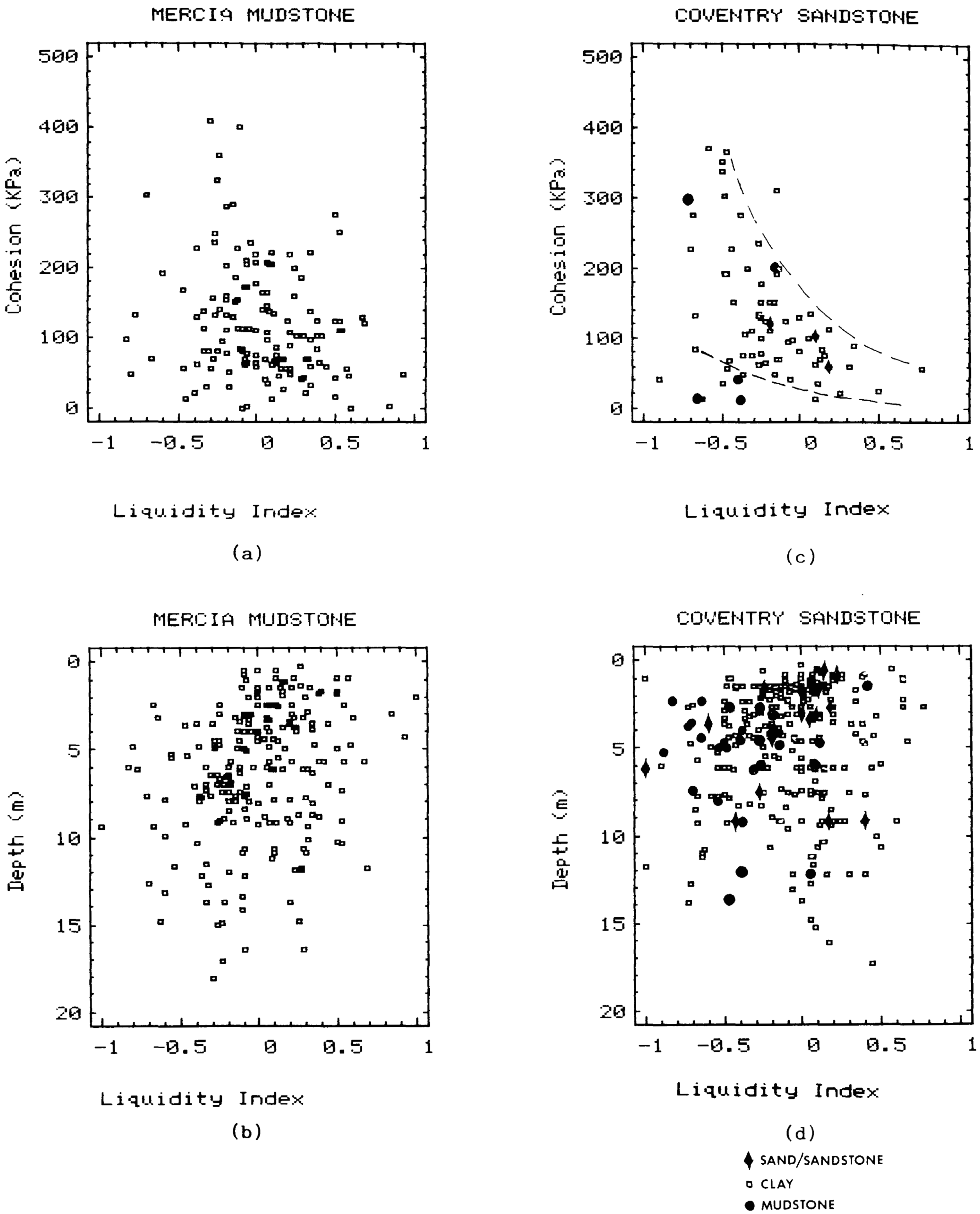


Figure 22a,c Cohesion vs Liquidity index for Mercia Mudstone and Coventry Sandstone. **b,d** Depth vs Liquidity index for Mercia Mudstone and Coventry Sandstone of Mercia Mudstone may be encountered to depths in excess of 10 m, and its influence has not been demonstrated. Most Mercia Mudstone clay data show weathering zones III and IV (Chandler, 1969), with zone I material rarely encountered at depths shallower than 18 m. There appears to be considerable overlap in the ranges of plastic limit, liquid limit, and their derivative parameters between weathering zones III and IV. Too few data for zones II and I were found to make any clear comparison. Unfortunately most site investigation reports make no reference to weathering zones or grades. The arithmetic mean specific gravity for Mercia Mudstone was found to be 2.70.

Bands of siltstone and sandstone (e.g. Arden Sandstone) within the Mercia Mudstone are poorly represented in the geotechnical data base.

Drift deposits

Drift deposits are represented in the geotechnical data base by boulder clay (undifferentiated), Wolston Clay, Baginton Sand and Gravel, Glacial Sand and Gravel (undifferentiated), laminated lake clays (undifferentiated) and alluvium (undifferentiated). The great majority of the boulder clay data refers to the Thrussington Till, which is derived largely from Triassic rocks. Most of the Glacial Sand and Gravel data are from the Wolston Sand and Gravel.

Approximately 70% of the geotechnical data for the drift are from the boulder clay and Wolston Clay units. Casagrande plasticity plots and moisture/density plots for these are given in Figures 9a, 9b, 9d and 9e. The relationship between moisture content and depth is shown in Figures 11a and 11b. The boulder clay plasticity plot shows that the bulk of the data fall within classes CL and CI. However, a significant number of points fall within class CH (high plasticity), and the liquid limit histogram shows a small cluster of points around a liquid limit of 50%. These may represent a boulder clay of different lithology to the rest. The linear regression 'T-line' for the boulder clay plasticity plot data is: PI = 0.70 (LL - 8.4), for which r = 0.94. This corresponds closely to those reported for modern englacial debris and undisturbed lodgement till (PI = 0.77 (LL - 10.5), Boulton and Paul, 1976), and for Anglian lodgement tills (PI = 0.71 (LL – 9.9), Little and Atkinson, 1988). The T-line is largely a function of a grain-size distribution (with clay content increasing from left to right along the T-line), whilst sorting or mixing in deposits such as flow tills, tends to move points away from the T-line (Boulton and Paul, 1976).

The plasticity plot for Wolston Clay (Figure 9b) shows the points falling very close to a T-line defined as: PI = 0.84 (LL - 13.4) for which r = 0.98, despite a wide range of liquid limit values (22% to 88%). The moisture content v dry density plot (Figure 9e) shows a similarly narrow linear distribution. These plots suggest a degree of homogeneity of particle size distribution and mineralogy within the Wolston Clay. Unfortunately very few particle-size determinations were obtained for either the boulder clay or the Wolston Clay to confirm this. The Wolston Clay is the only unit in the study having a statistically significant number of data points within the CV plasticity class (i.e. very high plasticity), and this contrast with other formations shows clearly in Table 4. The T-line for the Wolston Clay has the steepest gradient (0.84) of all units, which may also indicate the presence of high plasticity clay minerals.

Commercial data for the Glacial Sand and Gravel is sparse. Detailed accounts dealing respectively with the areas between Coventry and Rugby, and between Wroxall and Meriden are found in Crofts (1982; Figure 12), and Cannell (1982) and Cannell and Crofts (1984). The Baginton Sand and Gravel is the oldest drift deposit and consists of well-rounded, well-sorted, dominantly quartzitic gravels overlain by well-sorted, fine to medium, slightly clayey and silty sands (mean grading: 10% fines, 73% sand, 17% gravel). A further unit of glacial sand and gravel (undivided) includes the younger Wolston Sand and Gravel, interbedded with the Wolston Clay, and consists mainly of silty and clayey fine sand (mean grading: 22% fines, 76% sand, 2% gravel). The gravel component is mainly well-rounded sandstone and quartzite with tabular mudstone. In the west of the study area the glacial sands and gravels are more coarsely graded (mean grading: 12% fines, 63% sand, 25% gravel) and are often coated with iron oxides giving a reddish or yellowish colour.

'Alluvium' (undivided) includes River Terrace deposits (First to Fourth terraces). A plasticity plot (Figure 9c) shows that most data lie in classes CL and CI, with only a few in the higher plasticity classes. A moisture/density plot (Figure 9f) shows a wide scatter of moisture content data, and hence the liquidity index also varies greatly (Figure 21b).

CHEMICAL TESTS

The few chemical test data, which have been located for this study area, are confined to sulphate content, in terms of total SO_3 in soil or in groundwater (Table 7c), and pH. Statistically significant sulphate and pH data have been found for the Coventry Sandstone and Mercia Mudstone, with a small data set for the boulder clay. Soil sulphate contents are entered in the geotechnical data base as grades 1 to 5 (Anon 1972, table 11; see Table 7c), rather than as discrete values. Data for sulphate in groundwater are not included in the database. Data for pH are quoted as discrete values.

The sulphate data for the Coventry Sandstone range from 0.01% to 0.1% (arithmetic mean 0.046%, SD = 0.025, n = 40) which places them entirely within grade 1 (Anon 1972), i.e. the lowest sulphate content, and for which ordinary Portland cement is permitted in construction. However, for the Mercia Mudstone, sulphate values range widely from 0.01% to 4.4%, the higher values resulting from gypsiferous bands within the mudstone. ('Pure' gypsum beds are not included in the database). Therefore the Mercia Mudstone includes all five sulphate grades (Anon 1972); grades 3 to 5 require special sulphate-resisting cements in construction, and grade 5 also requires a protective coating to concrete. Gypsum nodules are also recorded in the mudstone bands of the Bromsgrove Sandstone. Boulder clay sulphate data lie within grades 1 and 2 (values ranging from 0.01% to 0.4%). Sulphate values for the Keele Formation range from 0.02% to 0.2% (grade 1).

Arithmetic mean pH values for the Coventry Sandstone and Mercia Mudstone are 7.2 and 8.5 respectively.

Carbonate contents ranging from 2% to 20% are recorded for Mercia Mudstone outside the study area (Sherwood and Hollis, 1966; Chandler, 1969), the carbonate decreasing with increasing weathering. Free iron oxide contents for Mercia Mudstone were found by Sherwood and Hollis (1966) to range from 0.5% to 2.1%. The iron oxide is responsible for the red colouration and possibly for the aggregation observed in the Mercia Mudstone. The presence of 'swelling chlorite' is described in Perrin (1971) as well as chlorite mica, and possibly sepiolite. In a detailed mineralogical study of the Mercia Mudstone, Jeans (1978) describes X-ray diffraction analyses of samples from Jackson's Brickworks, [205 829]. Here calcite contents are low (less than 7%), whereas dolomite contents are high (up to 35%). Jeans (1978) demonstrates the presence of two clay assemblages of different origin within the Mercia Mudstone: a matrix assemblage of mica and chlorite (common to the Mercia Mudstone nationally), and an exotic, secondary, assemblage of magnesium-rich clay minerals (of limited occurrence) which includes sepiolite, smectite, palygorskite, chlorite, corrensite and irregular mixed-layer smectite/mica and smectite/chlorite minerals.

STRENGTH TESTS

This category is confined almost entirely to laboratory triaxial compression tests (UU or QU types), standard penetration tests (SPT) and rock penetration tests (RPT). In addition, there are a small number of point load rock tests, and laboratory Shear Box tests. Triaxial, SPT and RPT test data are summarized in Table 4. Triaxial and SPT data for selected formations are shown in Table 5 as modified 'box and whisker' diagrams; in Figures 22a, 22c and 23a-d, as plots of undrained cohesion (Cu derived from the triaxial test) v liquidity index; in Figures 6a, 6c and 10a-d as plots of cohesion v depth, and in Figures 6b, 6d and 7a-d as plots of SPT v depth.

The relationship between cohesion and liquidity index appears to follow an inverse exponential function; as the liquidity index increases towards a value of 1 (i.e. where moisture content = liquid limit) the cohesion reduces towards zero. This is best demonstrated by the boulder clay and Coventry Sandstone plots (Figures 23a and 22c), where the 'envelope' of data is indicated by a dotted line. The greater scatter of data points at low and negative liquidity index values, common to all units, is probably due to factors associated with stiff overconsolidated clays, such as fissuring, and sensitivity to specimen size in triaxial testing.

In many site investigation reports triaxial tests were found to be poorly executed and poorly interpreted; these have not been included in the database. However, when only the interpreted data, i.e. Cu and ϕ_u, are quoted some judgement is required in placing confidence in these values. Theoretically, an unconsolidated undrained triaxial test should produce a value for the angle of internal friction (ϕ_u) of zero. Positive values for ϕ_u may be due to non-homogeneity between samples, poor interpretation of test data, poor test procedure, or fissuring or partial saturation of specimens. With the exception of 'alluvium', all units exhibit a trend of increasing cohesion with depth, though with considerable scatter. A similar trend is observed in the SPT v depth plots. (The sharp 'step' in the SPT v depth plot for Coventry Sandstone, Figure 6b, is possibly the result of a lithological bias in the sampling). Correlations between SPT and triaxial strength are not included as these two parameters are rarely determined at the same horizon. Strictly speaking, SPT values should only be quoted in the range 0 to 50 (blows per 0.3 m penetration). However, much higher values (up to 1000) are often extrapolated from penetrations less than 0.3 m, or alternatively, the RPT is used which gives the penetration (in mm) for 50 blows with the SPT apparatus, and care is required, therefore, in analysing these data. Extrapolated SPT values have been included in the database, but as shown by Figure 6b for Coventry Sandstone, the reliability of these data, particularly at shallow depths, is questionable. Ideally SPT values should not be used to predict shear strength in cohesive soils (Carter, 1983). However, Stroud and Butler (1978) do suggest a Cu/SPT ratio of 4 to 6 for boulder clays.

Weathering tends to reduce the shear strength of mudrocks to a common value irrespective of lithostratigraphy (Cripps and Taylor, 1981). However, with unweathered mudrocks the major control over strength is overconsolidation, fissuring and present overburden. Hard clays and weak mudrocks, such as the Mercia Mudstone, are particularly susceptible to sample disturbance, especially in zone III (Davis, 1971), resulting in widely scattered data. Zone I Mercia Mudstone may be considered as a heavily overconsolidated soil, its dense state giving rise to high effective stress parameters (not recorded in the database). The behaviour of the more weathered Mercia Mudstone (zones II to IV) is more typical of lightly overconsolidated soils (Chandler, 1969). Highly weathered Mercia Mudstone (zone IV) may be comparable in some respects with normally consolidated clays. The extent to which other formations follow this behaviour is discussed later. Weathering zones, such as those shown in Figure 6c, are tentative, and do not necessarily reflect first hand descriptions from site investigation reports which make use of an arbitrary, weak rock/hard soil boundary at an SPT of 100.

Strength data for non-cohesive soils and rocks are very sparse. A small number of point load test results, found for sandstones and mudstones of the Coventry Sandstone, have been interpreted in terms of unconfined compressive strength, and show a range from 1 MPa for weak mudstones up to 100 MPa for extremely hard sandstones. These results are not directly comparable with the triaxial test data, as the point load apparatus tests intact specimens, often in a partially dry state.

The main link between shear strength and index properties for cohesive soils is with moisture content and plasticity, here expressed in terms of liquidity index. A link between change in shear strength behaviour and a threshold plasticity index value of 25% has been established (Vaughan and Walbancke, 1978) that is approximately the boundary between plasticity classes CI and CH. No residual strength data have been located for the study

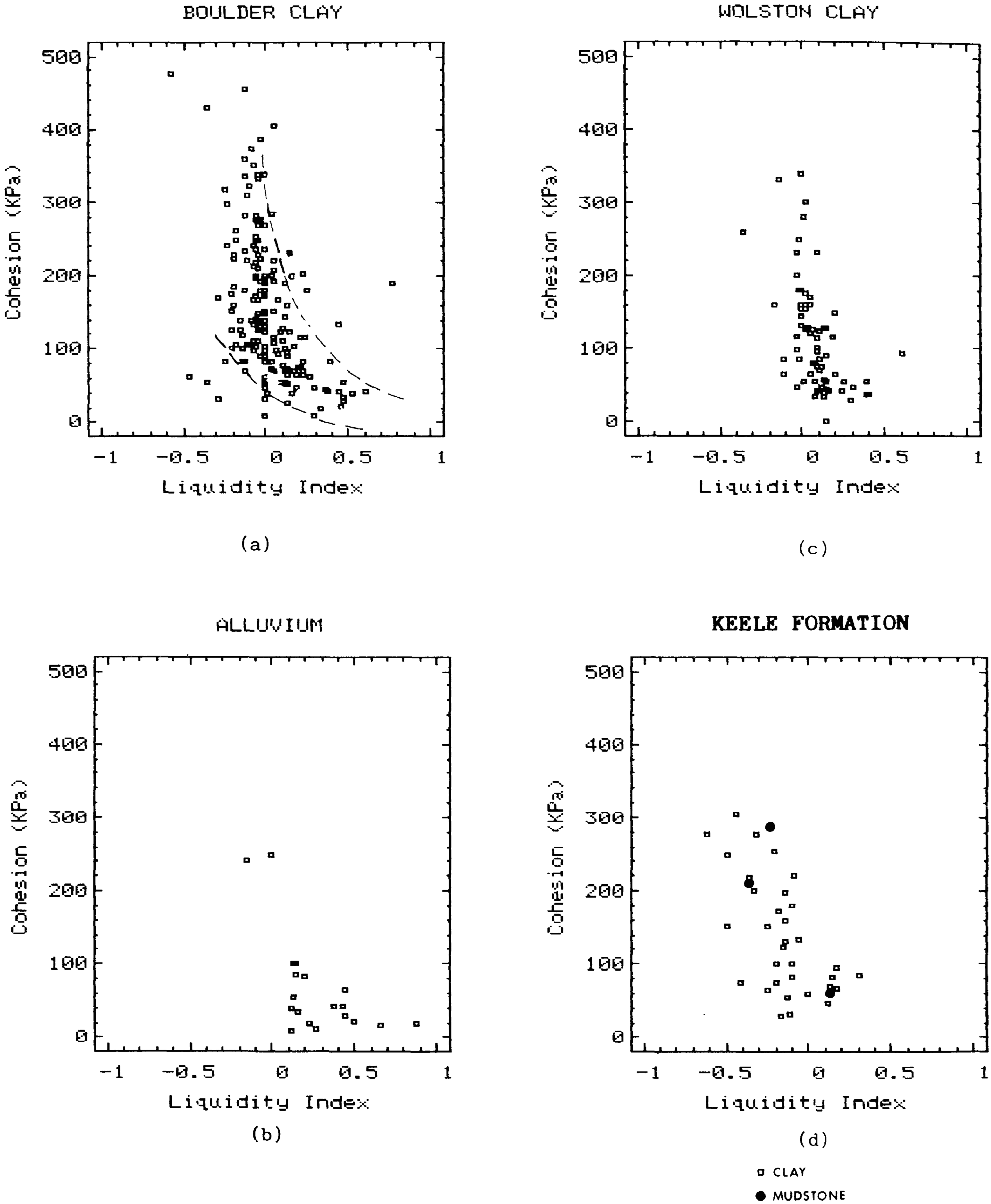


Figure 23a-d Cohesion vs Liquidity index for Boulder Clay, Alluvium, Wolston Clay and Keele Formation area. Chandler (1969) quotes values for ϕ'_r of between 18° and 30° for Mercia Mudstone and reports that residual strength is a function of both clay content and mineralogy.

For 'weak' sandstones, defined as having a saturated unconfined compressive strength in the range 0.5 to 20.0 MPa (Dobereiner and de Freitas, 1986), strength is largely a function of saturation rather than mineralogy. Small increases in moisture content of a few percent, from a dry or near dry condition, may more than halve unconfined compressive strength.

Cole and Stroud (1976), describing socket piles in Coventry founded on Coventry Sandstone, highlight the importance of creep deformation in sandstones with foundation loads of the order of 3 MPa.

CONSOLIDATION AND COMPACTION TESTS

Consolidation data for the study area are sparse. Results of 1-dimensional oedometer tests have been recorded in the data base as classes (1 to 5) of coefficient of consolidation (Cv) and coefficient of volume compressibility (Mv) (Table 7a and b). Data for Coventry Sandstone show Mv classes 1 and 3 exclusively (i.e. very low and medium compressibility) and Cv classes 3 and 4. For Mercia Mudstone the Mv classes are 1, 2 and 3, and the Cv classes 2, 3 and 4; median values being 3 (medium) and 3 (medium) respectively. For boulder clay, classes 2, 3 and 4 for both Mv and Cv are found, whilst for Wolston Clay Mv and Cv classes are 2 to 3 (low to medium) and 3 respectively. Data for alluvium, though sparse, range from class 2 (low) to 5 (very high) for Mv, and 2 to 3 for Cv.

The available data may be summarised as follows:

	Mv classes*					Cv Classes*				
	1	2	3	4	5	1	2	3	4	5
Coventry Sandstone	----		----					----	----	
Mercia Mudstone	----	----	----				----	----	----	
Boulder Clay		----	----	----			----	----	----	
Wolston Clay		----	----					----		
Alluvium		----	----	----	----		----	----		

*Refer to Table 6

Mv: → Increasing compressibility; Cv: → Increasing rate of consolidation

Class 1 (very low) compressibility, is confined to the highly overconsolidated clays/mudstones of the Mercia Mudstone and Coventry Sandstone. Compressibilities for boulder clay of 3 and 4 probably represent weathered material. The wide Cv range for alluvium is due to its characteristic heterogeneity. The lack of extremes (classes 1 and 5) on the Cv scale is common to all units tested.

Compaction and California bearing ratio (CBR) data mainly apply to the Coventry Sandstone, boulder clay and Mercia Mudstone with a few data for the Baginton Sand and Gravel. Chandler and others (1968) report that for Mercia Mudstone the CBR value is very sensitive to placement moisture content as is the stability of Mercia Mudstone fill generally. Difficulty in the compaction of hard 'marls' and similar mudrocks in the U.K. has been widely reported. Correlations between optimum water content and maximum dry density are shown in Figures 7a and b. Figure 7b confirms the influence on compaction behaviour of liquid limit. Figure 7a shows some separation of Coventry Sandstone data points according to lithology.

The wide variety of sample types which can be used in the CBR test has cast some doubt over much of the CBR data available for the study area, as test reports often do not clarify the precise test conditions. CBR values may be estimated from standard compaction data (Head, 1982).

ROCK MASS DATA

Information about rock mass properties in the database is limited to Rock Quality Designation (RQD = length of sound rock recovered >100 mm as a proportion of length of core run) and a fracture index (= no. of fractures per metre of core). This version of fracture index (sometimes referred to as FI or F) appears to be the inverse of the 'fracture spacing index', I_f (Franklin and others, 1971) which is expressed in mm. By far the largest amount of data is for the Coventry Sandstone (200 records) and Mercia Mudstone (46). Fracture values are given an upper ceiling of 50 which makes statistical treatment difficult. RQD however is expressed as a percentage and is traditionally classified (Deere, 1964) as follows:

RQD (%)	Description
0 – 25	very poor
25 – 50	poor
50 – 75	fair
75 – 90	good
90 – 100	excellent

Analysis of the data shows that for Coventry Sandstone RQD values cover the full scale range from very poor to excellent. This applies to all lithologies: sandstone, mudstone and clay. Taken overall, the arithmetic mean RQD for Coventry Sandstone is 48% (though disproportionately large numbers of points fall at 0% and 100%). This compares with a mean RQD for Mercia Mudstone of 36%. The wide ranges are due to both lithological variation, and structural features such as fissures and laminations within the clays and mudstones, and fracture zones within the sandstones. Sub-vertical and curviplanar joints, and conchoidal fractures, are reported within the Mercia Mudstone and other cohesive units. Due to the influence of coring technique and quality, it is difficult to compare RQD and fracture spacing values from different site investigations. Wide variations are reported in RQD and fracture spacing values found for adjacent sites in the same horizon.

APPENDIX III

GLOSSARY OF GEOTECHNICAL TESTS QUOTED IN THE DATABASE AND THEIR APPLICATIONS

FIELD TESTS

Standard Penetration Test (SPT)

The standard penetration test (SPT) is a dynamic test carried out at intervals during the drilling of a borehole (Anon, 1981). A standard 50 mm diameter split barrel sampler is driven into the soil at the bottom of the hole, for a distance of 450 mm, by the blows of a standard weight (65 kg), falling through a standard distance (0.76 m). The number of blows (N) required to drive the last 300 mm is recorded. A modification of the test for hard material and coarse gravel uses a solid cone instead of a cutting shoe, and is called a cone penetration test (CPT).

Although this is a field test which is subject to operational errors, the SPT is widely used to give an indication of the relative density of granular soils (very loose to very dense), and the consistency of cohesive soils (very soft to hard). Correlations have also been made between SPT and the bearing capacity of a soil.

The results of the SPT are meaningful up to and including an N-value of 50, corresponding to very dense granular soils and hard cohesive soils. The SPT is also frequently used in harder materials, ie. rocks and heavily overconsolidated soils or 'mudrocks', though the test is normally terminated before the shoe has been driven the full 300 mm. Rather than extrapolate the number of blows to represent the full 300 mm of test, the penetration in mm for 50 blows can be quoted. When the results are given in this manner the test is referred to as the Rock Penetration Test (RPT). The relationship between the two methods of quoting the results is tabulated below:

Relative Density/Consistency	SPT	RPT
Very loose/very soft	0 – 5	
Loose/soft	5 – 10	
Medium dense/firm	10 – 30	
Dense/stiff	30 – 50	
Very dense/hard	⩾ 50	⩽ 300
Rock/Heavily overconsolidated soils		200 – < 100

Rock Quality Designation (RQD)

Rock quality designation (RQD) was introduced (Deere, 1964) to give an indication of rock quality in relation to the degree of fracturing from drill cores. It is defined as the sum of the core sticks in excess of 100 mm in length, expressed as a percentage of the total length of core drilled. The parameter takes no account of the degree of fracture opening, or the fracture condition, and does not distinguish between fracture spacings of more than 100 mm. RQD has been used with uniaxial compressive strength to give an indication of excavatibility, and as one input for the classification of rock masses to assist in the design of tunnel support systems (Bieniawski 1974, Barton and others 1974).

Fracture Spacing Index (I_f)

Fracture Spacing Index is defined (Franklin and others, 1971) as the average length of core pieces; that is, unit core length divided by the number of fractures in it.

LABORATORY TESTS

Index Tests

Moisture Content

The moisture content of a soil sample is defined as the ratio of the weight of water in the sample to the weight of solids, normally expressed as a percentage, ie:

$$\text{Moisture content, } m = \frac{\text{weight of water}}{\text{weight of solids}}$$

Standard test procedure is given in Anon (1975). Moisture content is a basic soil property and influences soil behaviour with regard to compaction, plasticity, consolidation and shear strength characteristics.

Atterberg or Consistency Limits (Plasticity Tests)

As moisture is removed from a fine-grained soil it passes through a series of states, i.e. liquid, plastic, semi-solid and solid. The moisture contents of a soil at the points where it passes from one state to the next are known as 'consistency limits'. These limits are defined as:

Liquid Limit (LL) The minimum moisture content at which the soil will flow under its own weight.

Plastic Limit (PL) The minimum moisture content at which the soil can be rolled into a thread 3 mm diameter without breaking up.

Shrinkage limit (SL) The maximum moisture content at which further loss of moisture does not cause a decrease in the volume of the soil.

The range of moisture content over which the soil is plastic is known as the plasticity index (PI), and is defined as:

$$PI = LL - PL$$

The factors controlling the behaviour of the soil with regard to consistency are: the nature of the clay minerals present, their relative proportions, and the proportions of silt, fine sand and organic material. A soil may be classified in terms of its plastic behaviour by plotting plasticity index against liquid limit on a standard plasticity (or Casagrande) chart. The consistency limits also give an indication of soil strength and compressibility. Test procedures are given in Anon (1975).

Density

Density mass per unit volume of a soil, may be measured in various ways.

The total or **bulk density** is the mass of the entire soil element (solids + water) divided by the volume of the entire element.

The **dry density** is the mass of dry solids divided by the volume of the entire soil element.

The **saturated density** is the mass of the entire soil element with its pore spaces filled with water (i.e. totally saturated) divided by the volume of the entire soil element.

Density measurements are simple if an undisturbed specimen of known, or easily measured, volume is obtained. If this is not possible in the field, the sand replacement method is used to determine the volume of a hole from which the soil sample is excavated, by filling with a measured quantity of dry, uniformly graded sand of known density. Density measurements are usually expressed as Mg/m^3 and full test details are given in Anon (1975).

Soil density measurements may be used to assess various earth loads such as soil mass, overburden pressure, surcharge pressure and earth pressure on retaining walls.

Specific Gravity

The specific gravity (or relative density) of a soil is the ratio of the weight of dry solids to the weight of an equal volume of water (i.e. the weight of water displaced by the solids). It is, therefore, a dimensionless parameter. Full test details are given in Anon (1975). Specific gravity is a basic soil property and represents an average for the particles of different minerals present in a soil sample. The parameter is used to enable calculation of other basic soil properties. For example: Taking specific gravity (G), moisture content (m), voids ratio (e) and degree of saturation (S) we obtain the useful relationship:

$$Gm = Se$$

Particle Size Analysis

The particle size distribution of a soil is determined by sieving and sedimentation. A sample of soil is dried, weighed and sieved to remove the fraction greater than 20 mm in size. It is then immersed in water with a dispersing agent such as sodium hexametaphosphate to break up soil aggregates. The sample is then wet sieved to remove particles less than 63 μm. The fraction retained on the 63 μm sieve is dried and passed through a nest of sieves of mesh size ranging from 20 mm to 63 μm. The fraction retained on each sieve is weighed and the cumulative percentage passing each sieve is calculated. A grading curve of percentage passing against sieve size is plotted.

The fines which passed through the 63 μm sieve are graded by sedimentation. A representative subsample is made up into a suspension with distilled water, placed in a tall jar and made up to a volume of 500 ml. It is then agitated vigorously and allowed to settle. Samples are removed by pipette from a given depth at specific times, dried and the contained solids weighed or, alternatively, hydrometer readings of the soil-water suspension are recorded at specific time intervals. The size distribution can then be calculated using Stokes' Law which relates settling time to particle size. The entire grading curve for coarse and fine material can then be plotted. Full details are given in Anon (1975).

Particle size distribution is used for classifying soil in engineering terms (Anon, 1981). Particle size distribution curves will give an indication of soil behaviour with regard to permeability, susceptibility to frost heave or liquefaction, and will give some indication of strength properties. Particle size analysis does not, however, indicate structure. For example a sandy clay and a laminated sand and clay, which may behave very differently in situ, may show similar particle size distribution in a bulk test sample.

Chemical Tests

pH

About 30 g of soil are weighed and placed in 75 ml of distilled water in a beaker. The mixture is stirred and allowed to infuse overnight. A glass electrode connected to a pH meter is then placed in the stirred mixture and the pH reading taken. The electrode and meter may also be used to determine the pH of groundwater samples; pH may also be determined colorimetrically. Details are given in Anon (1975).

The pH of soil or groundwater is important when designing concrete structures below ground surface. Ordinary Portland cement is not recommended in situations with a pH below 6, high alumina cement can be used down to pH 4 and supersulphated cement has been used to pH 3.5. Acidic groundwaters can also cause corrosion in buried iron pipes.

Sulphate

The sulphate content of soil is determined by leaching a weighed sample of soil with hydrochloric acid and precipitating the dissolved sulphate by the addition of an excess of barium chloride. The precipitate is then filtered, ignited in a furnace and weighed.

The sulphate content of groundwater or an aqueous soil extract is determined by passing the water through a column of strongly-acidic cationic exchange resin activated with hydrochloric acid. The groundwater or soil-water washings are collected and titrated against standardised sodium hydroxide solution, using a suitable indicator. From the amount of sodium hydroxide used during titration the quantity of dissolved sulphates can be determined and expressed in terms of SO_3 content, as grams per litre or as parts per 100 000 (see Table 6c). Full test details are given in Anon (1975).

It is important that the sulphate content of groundwater and soil is known, as ordinary Portland cement deteriorates in the presence of sulphate. Knowledge of sulphate concentrations enables a suitable sulphate resisting or high alumina cement to be used in appropriate concrete mixes for applications below ground level.

Strength Tests

Triaxial Compression Test

The triaxial compression test is the most widely used test for determining the shear strength of cohesive soils, and a number of different methods may be used depending on the application of the results.

In general terms, an undisturbed cylindrical specimen (usually 76mm x 38mm) is placed between rigid end caps and covered with a rubber membrane. The assembly is then placed in a triaxial cell which is filled with water, taking care that all air is removed. The confining water pressure in the cell is then maintained at a prescribed constant value while the axial load on the specimen is increased at a constant rate of strain. The test continues until the specimen shears or a maximum vertical stress is reached. Vertical displacement and axial load on the sample are measured during the test, which is repeated on two further specimens (from the same sampling point) at different confining pressures. From the results obtained from the three tests, a standard graphical construction (based on the Mohr-Coulomb failure criterion) enables the measured principal stresses to be plotted, so that the shear strength of the soil can be determined in terms of its cohesive and frictional components (i.e. cohesion, C, and angle of internal friction, ø).

The test may be carried out with the sample either drained or undrained (with or without pore pressure measurement), and the type of test will depend upon the site conditions and type of engineering works being undertaken.

An **unconsolidated-undrained (UU) test** is used for foundations on normally consolidated clay soils (where drainage would be slow). The test normally takes only a few minutes, as pore pressures are not allowed to dissipate, and is thus often known as a **quick-undrained (QU) test**. The strength parameters determined in this test are the total or apparent undrained cohesion, and friction values (C_u and $ø_u$, respectively).

In a **consolidated-undrained (CU) test**, free drainage of the specimen is allowed under the cell pressure for 24 hours before testing (that is, the sample consolidates). The drainage valve is then closed and the load increased rapidly to failure. This test is applicable to situations where a sudden change in load takes place after a period of stable conditions (e.g. as a result of rapid drawdown of water behind an earth dam).

A consolidated-undrained test with pore pressure measurement may also be carried out. In this test, the measurement of pore pressure enables calculation of the effective strength parameters, C'and ø' (sometimes referred to as the "true" cohesion and "true" angle of internal friction), in addition to the undrained parameters, C_u and $ø_u$.

A **drained (CD) test** is suitable for sandy soils, or for clay embankments in which drainage blankets have been laid. Free drainage of the sample is allowed during both the consolidation and loading stages of the test, with the sample loading applied at a rate slow enough to allow dissipation of pore pressures. The test conditions enable the determination of the effective strength parameters, C' and ø'.

Shear Box Test

A rectangular prism of soil is cut from an undisturbed sample and placed in an open-ended, square, metal box which consists of an upper and lower half bolted together. The sample is fitted top and bottom with perforated metal plates and porous stones top and bottom and the assembly placed in a trolley. A vertical load is applied to the sample via a hanger assembly. The bolts holding the upper and lower halves of the box are then removed, and the specimen is sheared by applying a horizontal force to one half of the box assembly. The magnitude of the shearing force and the displacement are measured, and the maximum shearing stress determined. The procedure is repeated several times with samples of the same soil at different vertical loads. From the combined results the apparent cohesion and angle of internal friction can be calculated.

The shear box test measures the same parameters, cohesion and angle of internal friction, as the triaxial compression test but does so in a manner which does not allow the drainage conditions to be controlled. Also the plane of failure is governed by the test apparatus not by the soil properties. The triaxial test is therefore preferred in most applications. However, the shear box test is more suitable for granular soils, and it is also able to accommodate greater displacements. Therefore, it is suited to determining the peak and residual strength parameters needed to assess slope stability of hillsides, and the landslips which may have taken place on them.

Consolidation and Compaction Tests

Consolidation Test

If a saturated cohesive soil is subjected to an increase in loading the pressure of the water in the pore spaces will increase by the same amount as the applied stress. The water will therefore tend to flow towards areas of lower pressure at a rate controlled by the soil permeability. The removal of water causes a decrease in volume of the soil, a process known as consolidation.

The consolidation parameters are measured in the laboratory by placing a disc of soil confined in a metal ring, in a water-filled cell. A constant normal load is applied to the disc and its decrease in thickness measured with time. When it reaches a constant thickness for a given load, the load is increased (usually doubled) and the readings repeated. The loading is continued depending on the soil type and the structure for which the data is required. The coefficient of volume compressibility, M_v (m^2/MN), can then be calculated. This is a measure of the amount of volume decrease that will take place for a given increase in stress. The coefficient of consolidation, C_v (m^2/year) is also calculated, and is a measure of the rate at which the volume change will take place for a given increase in stress.

Consolidation test results are important for foundation design, and calculating the likely settlements that will take place during and after construction. The test results also enable the planning of phased construction stages to allow full consolidation settlement (dissipation of pore pressures) to take place prior to successive load stages.

Compaction Test

The compaction test determines the moisture content (the 'optimum') at which a soil may be compacted to its maximum dry density. A quantity of soil (5 kg) is compacted in a standard mould, using a standard rammer (2.5 or 4.5 kg) which is dropped from a standard height (300 mm or 450 mm) a standard number of times (27). The density of the compacted soil is then measured and its moisture content determined. The procedure is then repeated using the same soil at different moisture contents. The dry density of the compacted soil is plotted against its moisture content, and the moisture content at which maximum compacted density may be achieved is read from the curve. Details are given in Anon (1975).

The results of the compaction test are used to determine the optimum moisture conditions at which to place a given soil as general or embankment fill.

California Bearing Ratio (CBR)

The California Bearing Ratio test is an empirical test carried out in the laboratory, or in the field, which compares the resistance of a soil to penetration by a standard plunger to the resistance to penetration shown by a standard crushed stone:

$$CBR = \frac{\text{Measured force}}{\text{`Standard force'}}$$

However, there are various ways of preparing samples for the test. The samples may be either undisturbed or remoulded. Remoulded samples may be compressed into a standard CBR (or Proctor) mould under a static load, or dynamically compacted into it, at the required moisture content, either to achieve a specific density or by using a standard compactive effort. Undisturbed samples may be taken on site in a CBR mould, either from natural ground or from recompacted soil such as an embankment or a road sub-base. Specimens may be tested in the mould as prepared (or as received), or after soaking in water for several days.

For soaked CBR tests on remoulded soil at maximum compaction, for example, the test normally involves a series of samples which are compacted in a 152 mm diameter mould at moisture contents around the optimum. A surcharge weight is placed on the soil which is then immersed in water for four days. The mould is placed in a load frame, and a plunger 48.5 mm in diameter is forced into the sample to a penetration of 2.5 and 5 mm. The CBR value is determined as the higher of the ratios of the resistance at 2.5 mm and 5 mm penetration to the standard resistance of crushed stone at the same penetrations. Details are given in Anon (1975).

The CBR value of recompacted soil is very sensitive to variations in moisture content and dry density. Some typical laboratory CBR values for British soils compacted at natural moisture content are indicated below:

Type of soil	Range of PI (%)	Range of CBR* (%)
Clay	40–70	1–3
Silty clay	about 30	3–5
Sandy clay	10–20	4–7
Silt	0	1–2
Sand (poorly graded)	NP	10–20
Sand (well graded)	NP	15–40
Sandy gravel (well graded)	NP	20–60

* Lower values relate to water table depth ≤600 mm below formation level. Upper values to water table>600 mm below formation level.
(From TRRL Road Note 29) NP = non-plastic.

In the field test, the plunger is jacked into the ground against the reaction of a heavy lorry. Field values are usually lower than laboratory values and the results of these in situ tests are not directly comparable with laboratory test results. The laboratory test in the CBR mould is recognised as the standard test. The results of the CBR test are used to assess the suitability of soils for use as base, sub-base and sub-grade in road construction.

APPENDIX IV
DATA SOURCES

Borehole Data

Sources of borehole data collected during this contract are listed below. Those marked with an asterisk * are major sources:

Applied Geology Ltd., Kenilworth
Birmingham University Geology Department
*British Coal, Central Area, Coleorton
*British Coal, Opencast Executive, Ashby-de-la- Zouch
*British Railways Board, Soil Mechanics Section, London
Courtaulds PLC., Coventry
*Coventry City Council
*Douglas Engineering, Birmingham
Dunlop Ltd., Coventry
Former West Midlands C C (data now held by
Birmingham City Council)
*Geotechnics Ltd., Coventry
*GKN Keller, Ryton, Coventry
Jaguar Cars Ltd., Coventry
Johnson, Poole and Bloomer, Dudley
Massey Ferguson Ltd., Coventry
National Rivers Authority (including
Severn Trent Water Authority)
Norwest Holst Soil Engineering Ltd., Leeds
*Nuneaton and Bedworth B C
Ove Arup Ltd., Birmingham
*Packington Estate Enterprises Ltd
Readymix Concrete Ltd., Nottingham
Rover Group, Coventry
*Sir Owen Williams and Partners, Birmingham
Solihull M B C
Steetley Brick and Tile, Stoke on Trent
Sub Soil Surveys Ltd., Manchester
Taylor, Boyd and Hancock, Leamington
Wardell Armstrong, Newcastle- under-Lyme
*Warwickshire C C
West Midlands Regional Health Authority
*Wimpey Construction UK, Birmingham
*Wimpey Laboratories, Hayes

The borehole data is catalogued in the BGS archive on individual 1:10 000 sheets, each catalogue consisting of a site map at 1:10 560 or 1:10 000 scale and a borehole register together with the individual records. The sheet numbers included in this study and the numbers of boreholes in each catalogue are listed below:

Sheet No.		Boreholes collected for this study	Total No. of boreholes
SP 27	NW	0	38
	NE	109	171
	SW	0	23
	SE	7	37
SP 28	NW	198	253
	NE	57	123
	SW	117	465
	SE	74	99
SP 37	NW	1998	2018
	NE	97	539
	SW	37	166
	SE	25	363
SP 38	NW	66	200
	SW	553	714
	SE	458	628
Totals		3796	5837

Geophysical Data

The only major holder of geophysical information is British Coal, Headquarters Technical Department, Stanhope Bretby. The data consists of geophysical logs for approximately 35 boreholes and numerous seismic surveys. This information is not available to the BGS archive, although access is provided by British Coal to geophysical borehole logs. The logs have been interpreted by British Coal and some by BGS.

An interpretation of the seismic data by British Coal, presented in a way which aided the geological mapping, was the subject of a separate sub-contract completed on 30 November 1987.

Geophysical logs for some wells are being compiled by the National Rivers Authority.

Mine Plans

Coal

Copies of all known colliery abandonment plans, together with working plans for the Warwickshire Coalfield, are held by British Coal, Central Area, Coleorton, and were freely available to BGS. Abandonment plans are held in the public domain by British Coal but are not available for public reference at BGS. There are approximately 130 plans at 1:2500 and 12 composite plans at 1:63 360.

Ironstone and Fireclay

Some mine abandonment plans for ironstone and fireclay are held by the Mining Records Officer, British Coal, Newstead, Nottinghamshire. A list of plans published in 1929 (Mining Dept, 1929) includes these and a number of others which were held privately. Whether any of the latter still exist is not known.Copies of all available plans have been placed in the BGS archive.

Geological Specimens

BGS

Petrological and palaeontological collections at BGS are catalogued on a 1:50 000 sheet basis, and are held by the respective specialist departments at Keyworth. Collections of specimens from individual boreholes are housed separately at the National Geosciences Data Centre, Keyworth. These collections are available for public reference by prior appointment.

Non-BGS

A small collection of Carboniferous fossils is held by the Warwickshire Museum, Warwick, and a catalogue is available. A smaller number of specimens is held by the Coventry City Museum and Art Gallery. A few complete cores of boreholes are held by British Coal, Central Area and Opencast Executive. These are working collections rather than a permanent archive, but are normally offered to BGS when British Coal wishes to dispose of them.

Hydrogeology

Hydrogeological data held by the National Rivers Authority consist of

(i) A data bank of all licensed wells, boreholes and springs. These licences give the permitted rates of abstraction, the specific location and the depth and diameter of the well or borehole from which abstraction is taking place. Abstraction data is confidential where it relates to individual industrial users.

(ii) A data bank of groundwater chemistry relating to all public water supply sources and a few selected industrial sources.

(iii) Limited data on long-term changes in groundwater levels.

Similar data is held by the British Geological Survey, Hydrogeology Research Group, Wallingford.

APPENDIX V
LIST OF OPEN FILE REPORTS

Each component 1:10 000 map in the study area has an equivalent Open File Report describing the geology of the map, and with an appendix listing all the boreholes and trial pits in the BGS database. Each report is in the series "Geological notes and local details for 1:10 000 sheets" and they are listed below. The more recent reports have been given BGS Technical Report numbers in the WA Series, and these are shown in brackets.

SP 27 NW	Berkswell and Balsall Common		R A Old, 1987
SP 27 NE	Coventry West	(WA/88/47)	R A Old, 1988
SP 27 SW	Wroxall		R A Old, 1987
SP 27 SE	Kenilworth		R A Old, 1987
SP 28 NW	Maxstoke	(WA/89/20)	R A Old, 1989
SP 28 NE	Fillongley	(WA/89/21)	J G Rees, 1989
SP 28 SW	Meriden	(WA/89/22)	M G Sumbler, 1989
SP 28 SE	Allesley	(WA/89/23)	J G Rees, 1989
SP 37 NW	Coventry Central	(WA/88/48)	R A Old, 1988
SP 37 NE	Coventry South-east	(WA/89/77)	M G Sumbler, 1989
SP 37 SW	Stoneleigh	(WA/88/49)	R A Old, 1988
SP 37 SE	Bubbenhall	(WA/88/50)	M G Sumbler, 1988
SP 38 NW	Bedworth West	(WA/89/24)	D Mc C Bridge, 1989
SP 38 SW	Coventry North	(WA/89/25)	R A Old. 1989
SP 38 SE	Coventry North-east	(WA/88/51)	D Mc C Bridge, 1989

Copies of these reports may be ordered from BGS, Keyworth, Nottingham, NG12 5GG.

APPENDIX VI
STATUTORY AUTHORITIES RELEVANT TO PLANNING AND DEVELOPMENT

Coal

British Coal
Central Area
Coleorton
Leicester
LE6 4FA

Responsible for current and future underground mining

British Coal
Mining Records Office
Newstead Colliery
Newstead
Nottingham
NG15 0DA

Responsible for plans of abandoned mine workings

Geology

Various Acts of Parliament ensure that all information obtained from the sinking of boreholes and shafts for minerals, including petroleum, and for water, is made available to the British Geological Survey.

Any of the following operations must, by Act of Parliament, be notified in writing to the British Geological Survey:

The sinking of a new borehole or shaft to a depth of more than 30 m (15 m for water), or the deepening of an existing borehole or shaft to a depth of greater than 30 m (15 m for water).

Any person carrying out these operations is also required to:

(a) *Keep a record of the nature and depth of the strata encountered,*

(b) *Retain specimens of cores and chippings for examination,*

(c) *Allow properly authorised officers of the British Geological Survey free access to specimens and records.*

For minerals, written notifications should be sent to:

The Manager
National Geosciences Data Centre
British Geological Survey
Keyworth
Nottingham
NG12 5GG

For water, written notifications should be sent to:

The Manager
Hydrogeology Research Group
British Geological Survey
Maclean Building
Crowmarsh Gifford
Wallingford
OX10 8BB

Applications for licences to drill or test pump boreholes for water should be sent to the National Rivers Authority.

Planning

County of West Midlands

City of Coventry[1]
Tower Block
Much Park Street
Coventry
CV1 2PY

Solihull Metropolitan Borough Council[1]
PO Box 24
Council House
Solihull
B91 3QS

County of Warwickshire

North Warwickshire Borough Council[2]
Council House
South Street
Atherstone
CV9 1BD

Nuneaton and Bedworth Borough Council[2]
Town Hall
Nuneaton
CV11 5AA

Warwick District Council[2]
1 Warwick New Road
Leamington Spa
CV32 5JD

Warwickshire County Council[3]
Shire Hall
Warwick
CV34 4RR

Notes:

1 Unitary Planning Authority with responsibility for all planning functions.

2 Planning Authority with responsibility for development control (excluding minerals and waste disposal) and local planning.

3 Planning Authority with responsibility for minerals, waste disposal and structure planning

Waste Disposal

City of Coventry
Broadgate House
Broadgate
Coventry
CV1 1NH

Enquiries to: Environmental Health and Trading Standards Department

Solihull Metropolitan Borough
PO Box 24
Council House
Solihull
B91 3QS

Enquiries to: Environmental Health and Trading Standards Department

Warwickshire County Council
PO Box 43
Shire Hall
Warwick
CV34 4SX

Groundwater Water Supply and Sewage Disposal (from 1st September, 1989)

National Rivers Authority
Sapphire East
550 Streetsbrook Road
Solihull
B91 1QT

All applications for licences to drill and test pump boreholes for water should be sent to the above address, and not to the British Geological Survey.

APPENDIX VII
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Typeset and Printed in England by Saxon Printing Ltd., Derby.