TECHNICAL REPORT WA/91/4

Applied geological mapping in the Wrexham area: geology and land-use planning

B A Hains

BRITISH GEOLOGICAL SURVEY

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Onshore Geology Series

Applied geological mapping in the Wrexham area: geology and land-use planning

B A Hains

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Cover illustration

The A483 from Chester to Wrexham (Gresford bypass) has been built through the northern part of the gorge of the River Alyn, partly through on soft alluvial sediments, and partly on waste from the now-disused Gresford Colliery.

This study was commissioned by the Department of the Environment, but the views expressed in it are not necessarily those of the Department

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

Geographical index

UK, Wales, Clwyd

Subject index

Land-use planning, thematic maps, resources, aggregate, mining, engineering geology, ground stability, hydrogeology

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PREFACE

This account describes the applied geology of the Wrexham area, encompassing 215 sq km. It covers the Ordnance Survey 1:10 000 Sheets SJ 24 NE; SJ 25 NE, SE; SJ 34 NW, NE; SJ 35 NW, SW, SE; and part of SJ 35 NE.

The northern part of the district was first geologically surveyed at the 1:10 560 scale between 1879 and 1885; the remaining area was completed, and the northern part partially revised, from 1910 to 1913. Publications on economic aspects of the district included a memoir on the metalliferous mining and mineral resources of the region (Smith, 1921) and two reports giving assessments of the sand and gravel reserves (Dunkley, 1981; Ball, 1982).

The present study was commissioned by the Department of the Environment on behalf of the Welsh Office. Funding was provided jointly by the Department of the Environment and the British Geological Survey. Its objectives were to produce updated geological maps at 1:10 000 scale, and, together with other available surface and subsurface data, to present the geological information relevant to land-use planning, development and redevelopment in the form of a set of maps at 1:25 000 scale with accompanying reports. A major aim of the study was to develop computer techniques so that the geological and thematic maps could all be computer generated on demand and in colour (Loudon et al., 1991) if required. Particular emphasis has been placed on drift deposits, underground workings and mineral resources. Syntheses of the engineering properties of the bedrock and drift (superficial) deposits of the area were undertaken (Waine et al., 1990). Limited testing of Coal Measure mudstones to determine their swelling characteristics has been carried out (Entwisle, 1989). A summary of the hydrogeology has been provided by Mr R A Monkhouse. Detailed resurvey at 1:10 000 scale, by Drs J R Davies and D Wilson, was limited to the Hope Mountain area; a desk study of the remainder of the area, including partial photogrammetric interpretation, and limited field checking was carried out by Drs R Addison (Leeswood Coalfield), B A Hains and I T Williamson (Sheet SJ 35 NE). Dr N J Riley provided palaeontological support for the Hope Mountain area. Dr D J Evans provided geophysical information pertaining to geological structures in the eastern part of the area. Data collection and computer coding of borehole logs was carried out by Mr J A Thorburn. The Project Leader was Dr B A Hains. Dr R A B Bazley, Regional Geologist for Wales, was the Nominated Officer for the British Geological Survey, and Mr D B Courtier, Welsh Office, was the Nominated Officer for the Secretary of State.

The ready cooperation of landowners and tenants, quarry companies, local authorities, governmental bodies and other holders of data during this survey is gratefully acknowledged. In particular we thank Clwyd County Council, Alyn and Deeside District Council, Wrexham Maelor Borough Council, British Coal, the Welsh Development Agency, Astbury Quarries Ltd, Dennis Ruabon Ltd, Alfred McAlpine Quarry Products Ltd, Tarmac Roadstone Ltd (North West) and Welsh Aggregates Ltd. We also acknowledge many geological and geotechnical consultants.

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EXECUTIVE SUMMARY

Introduction

The study area covers the northern part of the 'Denbighshire' Coalfield and its environs. It is centred on Wrexham, the largest town in North Wales. This area has been undergoing a transformation with the decline of coal mining and associated heavy industries and their replacement by an expanding service sector and new light and high-technology industries. Two other significant parts of the local economy, agriculture and the mineral extraction industry, continue to play an important rôle.

The decline of the coal industry has left a legacy of old workings, abandoned shafts and adits, and spoil heaps. Additionally there are many disused and extant workings for sand and gravel, limestone and brick-clay. This history of exploitation of mineral resources has given rise to variable ground conditions which can pose problems for development. Consequently there is a need for detailed up-to-date geological information to enable planning policies to be applied in the most cost-effective manner.

This study has examined and updated the existing geological and other databases, using newly developed computing techniques where applicable. The results are presented in a form intended to aid planners, engineers and geologists. Two sets of maps and four reports have been prepared:

1 The main report, on geology and land-use planning, with a set of ten thematic maps at the 1:25 000 scale.

2 A set of nine geological maps at the 1:10 000 scale.

3 Three other reports (published separately) on computing techniques (Loudon et al., 1991), engineering geology (Waine et al., 1990) and swelling characteristics of mudrocks (Entwisle, 1989).

The study was funded jointly by the Department of the Environment (on behalf of the Welsh Office) and the British Geological Survey (BGS). The work was carried out by BGS staff at the Aberystwyth, Edinburgh, Keyworth and Wallingford offices.

Objectives

The main objectives of the study were:

1 To produce a new set of geological maps at 1:10 000 scale of the entire area.

2 To produce a set of thematic element maps (mainly at 1:25 000 scale) and to collate various geotechnical and other available information in reports intended for use principally by planners and developers.

3 To develop computer techniques to enable the 1:10 000 geological maps, the thematic maps, graphic logs of boreholes and other information to be produced on demand and in colour where possible.

Geology

The area is dominated by sedimentary rocks of Carboniferous age, which lie unconformably on Ordovician rocks, and are themselves overlain unconformably by Permo-Triassic rocks (Figure 6). The Carboniferous sequence has, at its base, up to 225 m of limestone with subordinate mudstones and sandstones. This is overlain by up to 420 m of Millstone Grit sandstones and mudstones. These are in turn succeeded by up to 520 m of Productive Coal Measures characterised by a cyclic repetition of mudstone, siltstone, sandstone, seatearth and coal. The Productive Coal Measures are succeeded by up to about 900 m of 'Red Measures' (Upper Coal Measures). These also commonly show a cyclic repetition of strata, but coal seams are poorly developed. The succeeding Permo-Triassic sandstones (up to 540 m) are entirely covered by thick drift (superficial) deposits, of relatively recent glacial or post-glacial origin, as is most of the outcrop of the Productive Coal Measures and 'Red Measures'.

The strata have a general gentle dip towards the east, and in broad terms this is shown in the topography of the district. The high ground in the west reflects the outcrop of the massive limestones of the Carboniferous Limestone and the basal sandstone of the Millstone Grit. Eastwards there is a gradual slope towards the broad valley of the River Dee and the Cheshire-Shropshire plain; this slope is underlain by the softer, more easily eroded, and largely drift-covered mudstones of the various divisions of the Coal Measures and, finally, the sandstones of the Permo-Triassic.

Summary of geological factors related to land-use planning

Mineral resources

1 Sand and gravel is the most important mineral resource in the study area. It covers a wide area, especially around and to the north of Wrexham. Potential resource areas are delimited on Map 7, indicating where future development could give rise to sterilisation of deposits.

2 Limestone, of proven aggregate quality and purity, is present around Minera. Resources within the study area are limited. Resources of brick-clay are limited by thick drift overburden, and sandstone, while extensive, is not considered to be of major importance (Map 6).

3 Further deep mining for coal would not appear to be economically viable; however, despite extensive shallow mining in the past, potential for opencast extraction still exists within the area of the Productive Coal Measures outcrop where the drift thickness is less than about 30 m (Maps 5 and 10).

4 Most of the solid rock aquifers, apart from the Carboniferous Limestone, are to a large extent protected from pollution by a thick, relatively impermeable cover of drift; water supplies taken from the drift deposits are more easily contaminated (Figure 18, Maps 2 and 4).

Constraints to development

5 Much of the district has been mined for coal in the past. Shallow mining, restricted to those areas of the Productive Coal Measures outcrop with less than about 30 m of drift overburden, may still be a cause of instability or soft ground conditions. Deeper workings, in the eastern

part of the coalfield, are unlikely to cause problems. Over 1300 shafts and adits are known to exist; others undoubtedly remain unlocated (Maps 5 and 10).

6 Extensive mining for lead and zinc has taken place south and west of Minera. The extent of many of the workings is not known, and there are some 200 known shafts and adits. These may remain open at depth even if blocked at the surface (Map 5).

7 In general, solid rock, till and glacial sand and gravel provide reasonable foundation conditions below the weathered zone. Alluvial deposits and peat in river valleys and kettle holes, and peat on the western hill slopes have relatively weak geotechnical parameters (Maps 8 and 9).

8 Made ground is extensive and of variable composition. The infill of worked opencast sites and recently restored sand and gravel pits is usually well documented; earlier pits and quarries may have fill of unknown type and can give rise to foundation problems (Maps 2 and 10).

9 Old coal workings can act as areas for methane accumulation, and this gas can also accumulate in old, badly designed, landfill sites. Spontaneous combustion may occur under certain conditions if colliery waste is disturbed (Maps 5 and 10, Figure 18).

10 Steep slopes, especially in drift deposits or in the mudstones of the Millstone Grit and Productive Coal Measures may prove unstable, and several landslipped areas have been recorded. Further slips may occur if such slopes are disturbed either by human activity or undercutting by river erosion (Maps 1, 2 and 9).

11 Other potential constraints include environmental factors (e.g. the special landscape area, ancient monuments, nature conservation areas), possible flooding in the Dee valley, and high quality agricultural land (Figures 4 and 5).

The survey has resulted in considerable revision of the existing geological maps. The ten 1:25 000 scale thematic maps, nine new 1:10 000 scale geological maps, reports and computerised databases enable geological factors to be more accurately assessed in relation to land-use planning decisions. However, the study should not be used as a substitute for on-site investigation. In particular, where coal mining is suspected to have taken place the mine plans and shaft register held by British Coal should always be consulted.

INTRODUCTION

The data summarised in this report were obtained during a $2^{1}/_{4}$ year contract, commissioned in 1988 by the Department of the Environment on behalf of the Welsh Office. Funding for the work was shared jointly by the Department of the Environment and the British Geological Survey. The study area (Figure 1) is covered by parts of Sheets 108 (Flint), 109 (Chester), 121 (Wrexham) and 122 (Nantwich) of the British Geological Survey and lies entirely within the county of Clwyd. The component 1:10 000 maps are shown in Figure 2.

Objectives

The objectives of the project were to provide a cover of modern geological maps for the Wrexham area and, derived from this basic data, to present applied thematic information on geological conditions as they relate to planning and development. The work has complemented and extended information obtained during the Deeside contract (1985-88) covering the area immediately to the north. Additionally it has built upon earlier projects commissioned by the Department of the Environment aimed at developing cost-effective methods for computer production of maps for a variety of user requirements. The main aims of the project can be summarised as follows:

1 To carry out, where necessary, new basic geological field mapping; elsewhere to revise existing geological maps by the use of aerial photo-interpretation with limited field checking; from this data and other information to produce a new set of revised geological maps.

2 To collect and evaluate geological and geotechnical data from site investigation and other boreholes, from shafts and adits, and from other sources and to enter it into computer databases.

3 To present the geological and other data as thematic maps and reports in a form which can easily be understood by planners and other interested parties not trained in geology or related disciplines.

4 To develop new and existing computer techniques to allow the various databases to interact within a Geographic Information System so that the final thematic and geological maps and other information can be computer generated, in colour where applicable.

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

The use of this report and its limitations

The aim of the report is to provide geological information in a readily comprehensible form and assumes that some readers may have little geological or geotechnical background knowledge. Hence technical jargon is kept to the minimum. Since, however, some technical language is necessary, a glossary of terms is included to assist the reader.

The report is intended to act as a guide to other more detailed sources, e.g. the British Geological Survey archives of non-confidential boreholes and other data, including, most importantly, the

1:10 000 geological standards and original field-slips which are the fundamental sources on which much of the report is based. It is advisable that the maps and report are not used in isolation of one another. Each map has only a limited descriptive key and a fuller detailed description with relevant provisos is contained in the report.

This report and its constituent maps have been produced by the collation and interpretation of geological, geotechnical and related data from a wide variety of sources. Details of these various data sources are given in Annex B.

The maps provide only a general description of the nature and extent of factors relevant to the planning of land use and development. The data on which they are based are not comprehensive and their quality is variable, and the maps reflect the limitations of that data. Localised or anomalous features and conditions may not be represented, and any boundaries shown are only approximate. No information made available after 30th September 1990 has been taken into account. For these reasons:

This report and its constituent maps provide only general indications of ground conditions and must not be relied upon as a source of detailed information about specific areas, or as a substitute for site-investigations or ground surveys. Users must satisfy themselves, by seeking appropriate professional advice and carrying out ground surveys and site-investigations if necessary, that ground conditions are suitable for any particular land use or development. However, the report and maps are a valuable source of general information relevant to planning issues and provide a convenient background for those designing site investigations.

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

Boreholes and shafts registered with the British Geological Survey are identified by a four element code (e.g. SJ 35 SW/15). The first two elements refer to the relevant 10 km National Grid square, the third element to the quadrant of that square and the fourth to the accession number.

Data, including borehole logs, used in preparing this report and associated maps are lodged at the Aberystwyth office of the British Geological Survey. Any enquiries concerning these documents should be directed to the Regional Geologist for Wales, Bryn Eithyn Hall, Llanfarian, Aberystwyth, Dyfed SY23 4BY.

Presentation of results

Four reports have been prepared:

1 Applied geological mapping in the Wrexham area: geology and land-use planning [This report]

2 Applied geological mapping in the Wrexham area – computing techniques (Loudon et al., 1991)

3 Engineering geology of the Wrexham area (Waine et al., 1990)

4 The swelling characteristics of weathered Coal Measure mudrocks from Sydallt, near Wrexham, Clwyd, Wales (Entwisle, 1989)

Ten thematic element maps (at 1:25 000) scale and two thematic element figures (at 1:83 333 scale, in this report) have been prepared:

Maps

1 Solid geology

2 Drift geology

3 Rockhead elevation

4 Drift thickness

5 Mining activities – Coal/Metalliferous

6 Bedrock resources – except Coal/Metalliferous

7 Sand and gravel resources

8 Engineering geology – solid

9 Engineering geology – drift

10 Geological factors for consideration in land-use planning

Figures

18 Hydrogeology

19 Mineral resource potential

Nine 1:10 000 geological maps have been produced:

SJ 24 NE; 25 NE, SE; 34 NW, NE; 35 NW, NE, SW, SE

GEOGRAPHICAL AND PLANNING BACKGROUND

Geographical background

The study area (215 km^2) lies within the county of Clwyd. Its regional context is depicted in Figure 1. The component OS 1:10 000 sheets of the study area are shown in Figure 2, together with the outlines of the former 1:10 560 County Sheet grid which formed the topographical base for previous geological surveys of the area. Much of the archival material used in the report is also recorded on the County Sheet base. The generalised topography, drainage pattern and major towns are shown in Figure 3.

The area reaches its highest point (460 m) in the south-west, at the summit of Esclusham Mountain. This high ground, which extends northwards towards the R. Cegidog and thence north-east to Hope Mountain, reflects the outcrop of the Carboniferous Limestone and the basal sandstone of the Halkyn Formation. In the southern part of the study area, south of the Nant y Ffrith, there is a general easterly slope from Esclusham Mountain towards Wrexham. This is interrupted by a number of escarpments formed by sandstones in the Bettisfield Formation. These are most noticeable in the Brymbo - Gwersyllt area where the Cefn Rock forms two parallel ridges separated by faulting. In the drift-covered ground from Wrexham eastwards there is, overall, a very gentle easterly slope towards the broad valley of the River Dee. This slope is interrupted by many minor undulations and shallow stream valleys, and also by a marked eastward facing slope from Marford to Marchwiel at the eastern edge of the sand and gravel deposits of the 'Wrexham delta-terrace'. This southern part of the area is drained by the R. Clywedog and its tributaries. The general drainage is from west to east, but a number of minor streams trend approximately north-south. Moundy topography with some large enclosed hollows (kettle holes) partly filled with clay and peat is well developed between Gresford and Wrexham.

North of the Nant y Ffrith the topography is more complex, reflecting the greater complexity of the underlying geology. The general NNE slope of the terrain is interrupted by the low ground of the drift-covered Leeswood Coalfield between the north-west corner of the study area and Hope Mountain, and also by the NNW trending valley of the R. Alyn. This valley was initiated during late-glacial times between the margins of the Welsh and Irish Sea ice-sheets, and was the conduit for the melt-water which laid down the sand and gravel deposits around Wrexham, Llay and Gresford.

The main town is Wrexham, the largest urban centre in North Wales. To the north, west and south-west are the so-called 'urban villages', settlements originally based on coal mining and associated industries, such as Brymbo, Coedpoeth, Gwersyllt, Llay, New Broughton, Rhosllanerchrugog and Rhostyllen. Other small towns and villages include Bangor-is-y-coed, Caergwrle, Gresford, Hope, Minera and Rossett. The economy of the study area has seen rapid change over the last thirty years as the traditional industries of coal mining, steel making, and associated heavy industries embraced new technology and production methods. Enormous job losses occurred in manufacturing in the late 1970's. Out of this decline came a variety of positive measures resulting in a more diversified, modern and robust economy and in the alleviation of the

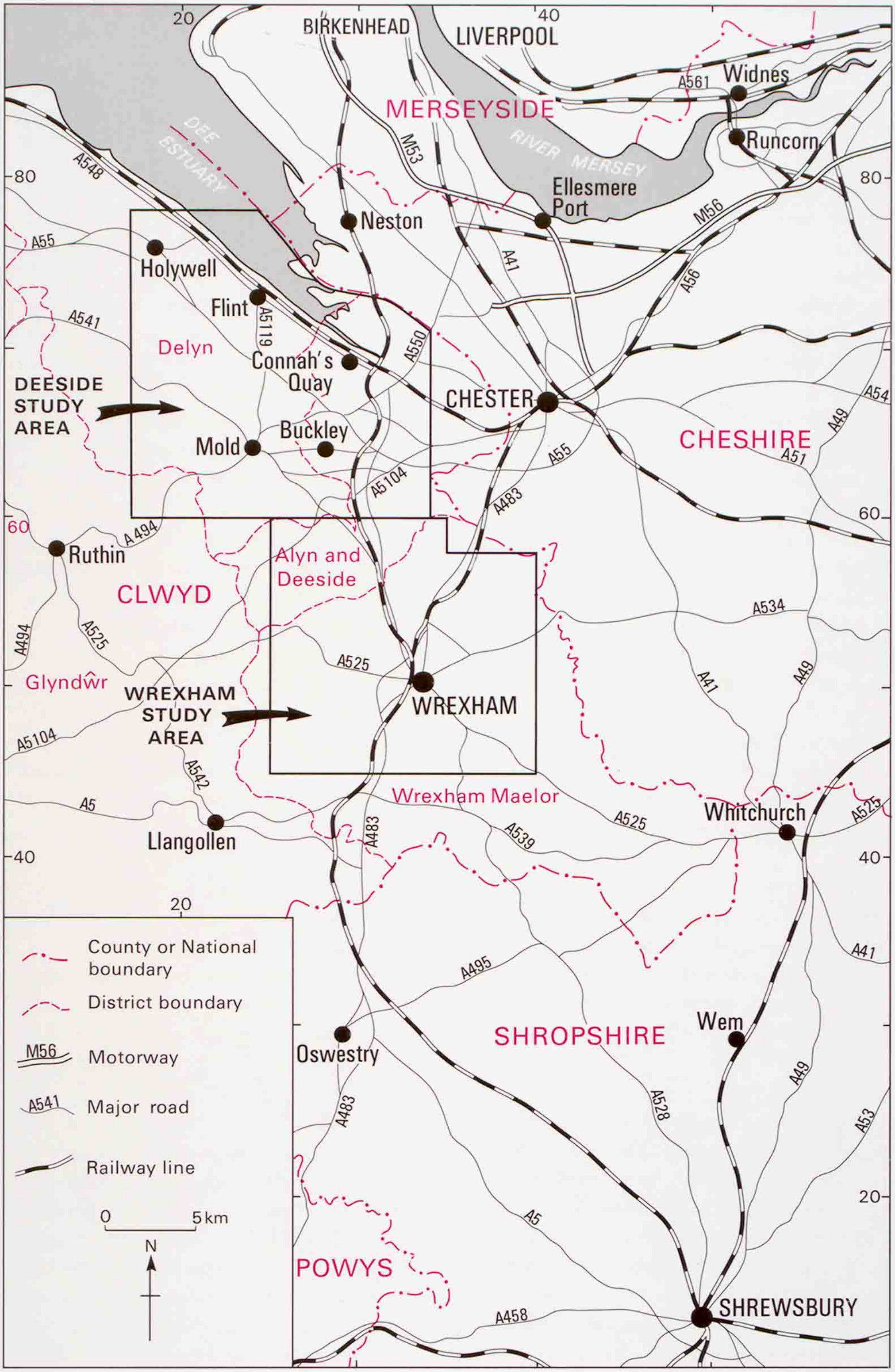
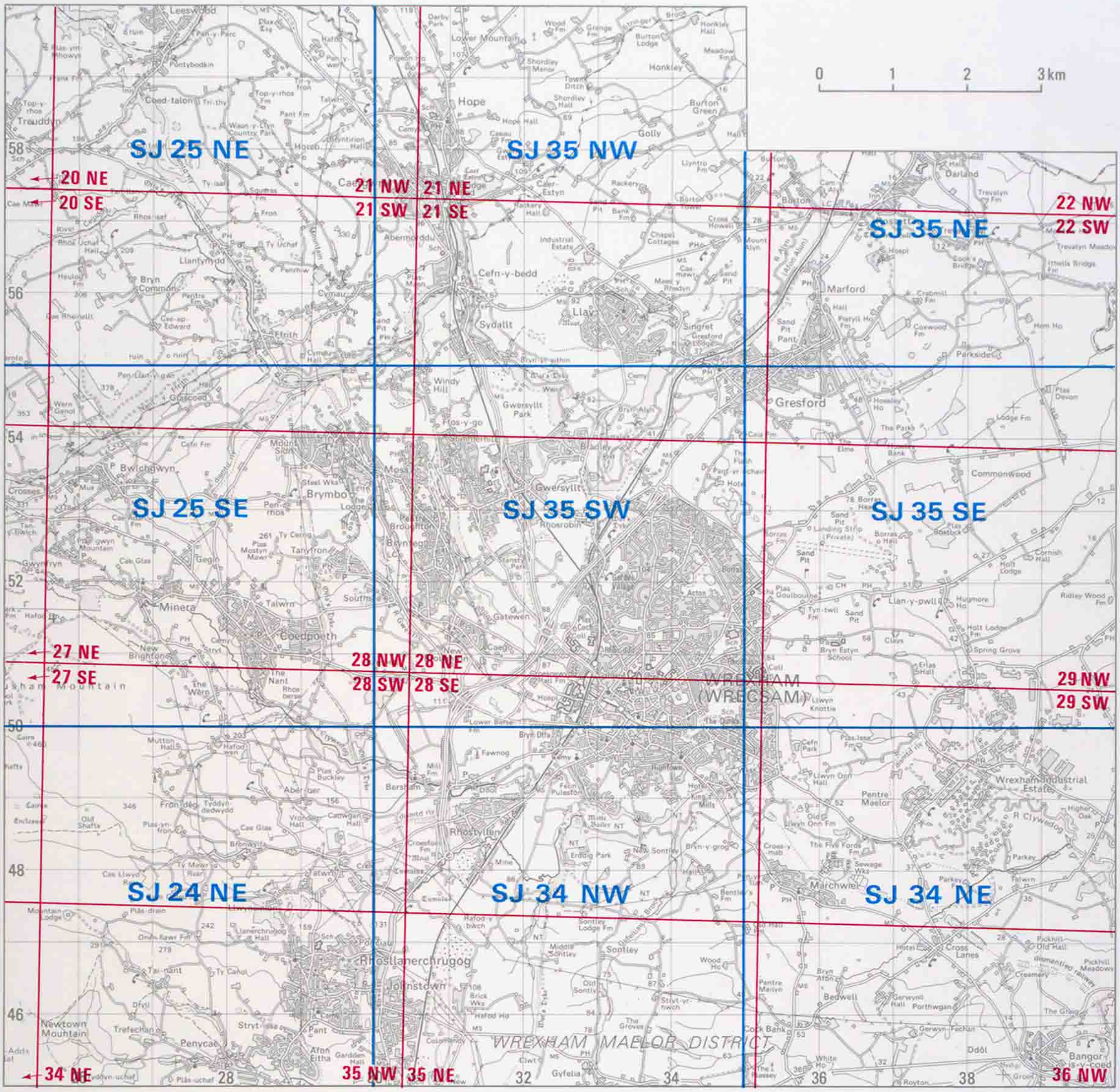


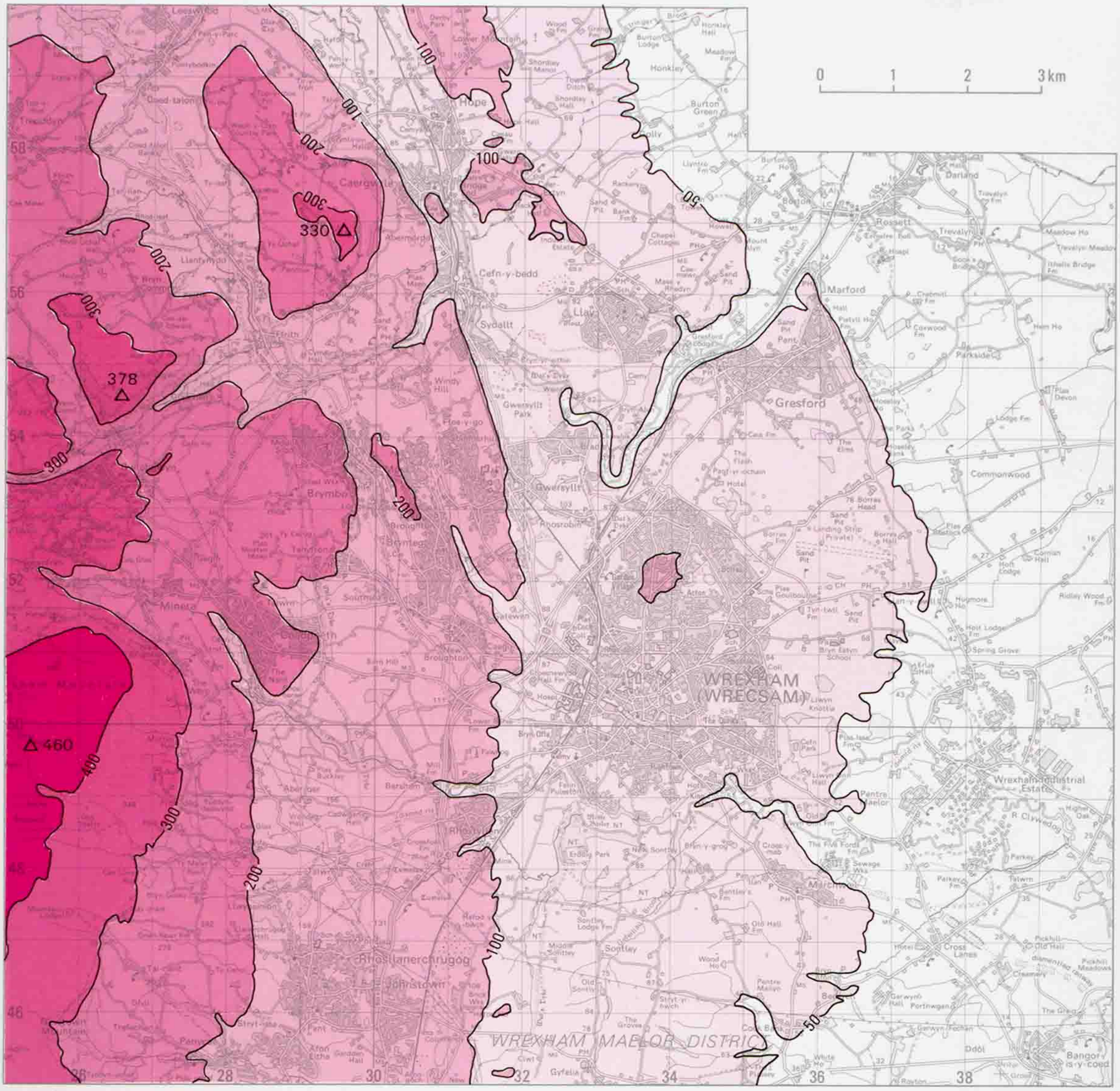
Figure 1 Sketch-map of the study area showing its regional setting



Boundary of component National Grid 1:10 000 Sheet identified thus: e.g SJ 34 NW

Boundary of component County Grid 1:10 560 Sheet (Denbighshire) identified thus: e.g 36 NW

Figure 2 Sketch-map showing the component 1:10 000 sheets of the study area and the outlines of the earlier County Sheet Grid



——100—— Contours in metres above O D

Figure 3 Topography and drainage of the study area effects of high unemployment and physical dereliction. A major industrial estate is located to the east of Wrexham, while the Wrexham Technology Park offers facilities for 'high technology' industries, research and development. Smaller new industrial areas are associated with many of the other towns and villages.

Two further significant parts of the local economy, namely agriculture and the mineral extractive industry, are likely to continue to play an important role. Agriculture is largely based on sheep farming on the high ground in the western part of the study area; further to the east, on the drift-covered Coal Measures and Permo-Trias, dairy and arable farming are more prevalent. The soils on this drift-covered land are very variable; the light and well-drained soils on the extensive sand and gravel deposits around Wrexham and Gresford contrast with the heavier clay soils developed on the till-covered ground to the south, east and west.

The main extractive industries are limestone quarrying and sand and gravel extraction. They are a major componment of the local economy, providing aggregate both for local needs and for the major conurbations of Merseyside, Greater Manchester and elsewhere (see 'Mineral working in Clwyd', 1982b). At present limestone is quarried at one site, sandstone at one site, and sand and gravel extracted from three sites. Since the closure of Bersham Colliery in 1987, coal extraction has been limited to small opencast sites, and further opencast production remains a possibility for the future. The Ruabon Marl is dug for tile-making at one site. Fireclay and brick clays have been dug and mined in the past and there has been extensive quarrying for sandstone in several areas. Mining for metalliferous ores, mainly lead and zinc, was formerly an important activity in the western part of the study area close to Minera.

Planning Background

Geology bears a relationship, directly or indirectly, to a variety of physical planning considerations, and is thus included amongst the numerous factors which need to be taken into account in allocating land uses to appropriate locations.

The main factors involved are as follows:

Supplies of mineral resources are essential to the economy but extraction of these can have adverse effects on the environment. Yet minerals can be worked only where they have been formed by geological processes. Planning of land use can direct future extraction to the least environmentally damaging locations but, for this to be possible, it is necessary to have general information on the types and extent of minerals present. Applied geological maps provide a broad indication of this. Conversely, minerals are a finite resource which will be needed by future generations. It is imprudent therefore to sterilise valuable resources by, for instance, building over them. Again mineral resource maps have a part to play in avoiding such sterilisation.

Land affected by underground, particularly shallow, mining may be liable to subsidence of the surface with consequent risks to property and people. Similarly some slopes may be subject to landsliding. Ground movements such as these may be triggered by natural processes or by human activity including excavation and construction. Most of these problems can be overcome by engineers but at a cost. Therefore caution is needed when developing or redeveloping land, and consideration of potential ground problems when planning land use is prudent. Applied geological maps assemble relevant background information in a form which can be readily used in both planning and in designing site investigations prior to development.

Underground water resources need to be safeguarded from pollution from, for instance, waste disposal or industrial sites. The pathways by which contaminants enter the ground are defined by the nature of the rocks, both unconsolidated and hard, beneath the soil. Applied geological maps highlight the properties of these materials and, thus, give general indications of where problems might occur.

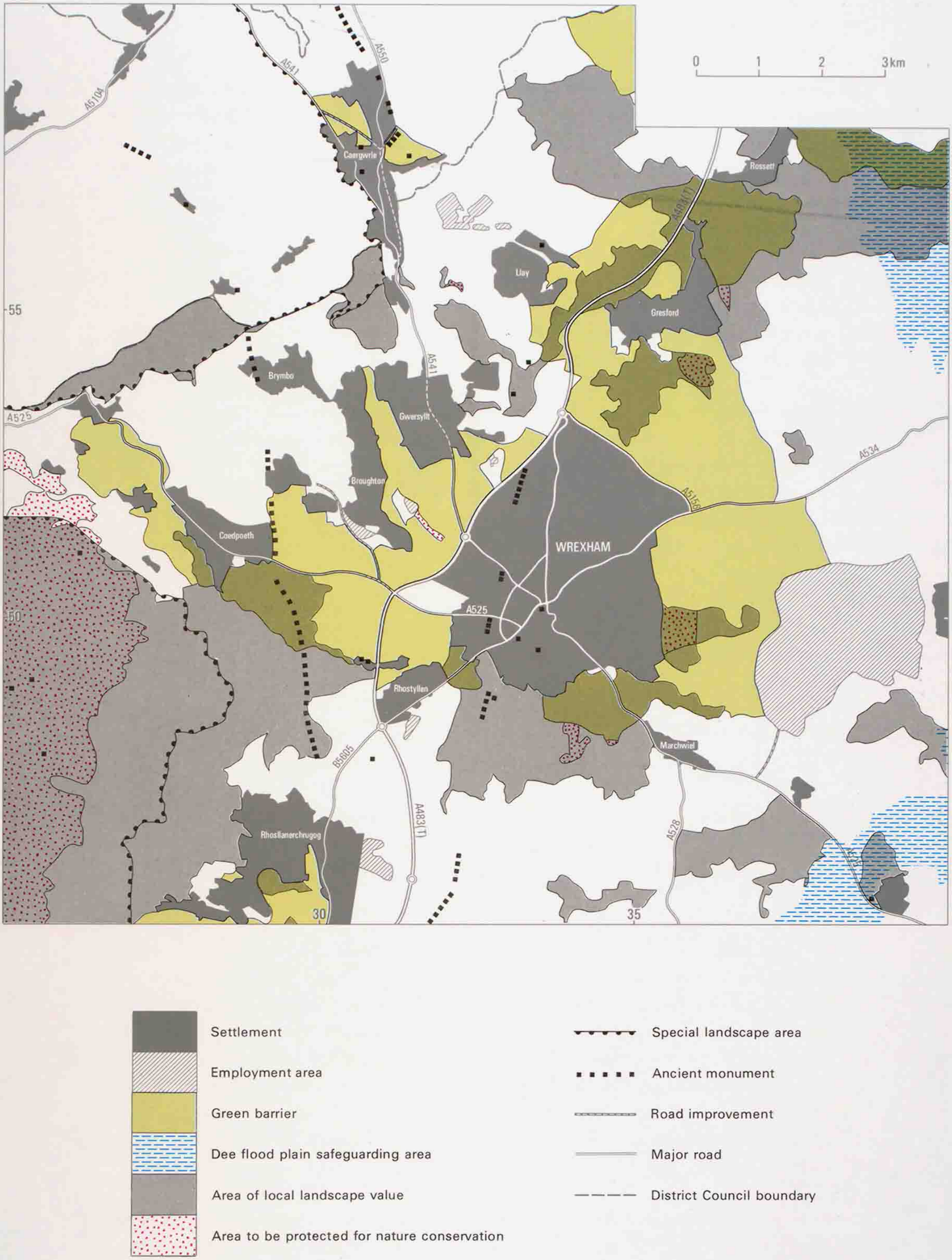
Low-lying land in river valleys may be liable to flooding. Development in such areas may be at risk. Maps showing the extent of such areas can guide thinking on the provision of precautionary works or on allocations of land for future development.

These four examples demonstrate the relevance of applied geological maps to planning, development and protection of the environment. Two of the examples relate to earth resources. The others concern constraints which might limit the potential for development or cause higher costs if development is carried out. The maps can be used alongside the broader range of information – social, economic, ecological, and so on – which is needed in making decisions on safe, cost-effective and environmentally friendly development.

National planning policies, other strategic guidelines, and Structure Plan policies set the broad framework for planning at the local level. The Structure Plan sets out, in broad terms, the general scale of future development on a county basis, and the policies which will be used to encourage and control it. It is the Local Plan which sets out detailed policies and specific proposals for the use of land, guides most day-to-day planning decisions and aims to ensure a balance between the needs of development and environmental conservation.

Guidelines for the preparation of structure and local plans, and their implementation through development control, are set out in a series of planning policy guidance notes (PPG's) and minerals policy guidance notes (MPG's) issued by the Department of the Environment and Welsh Office. Notes of particular relevance to planning and development in the area of study include those dealing with opencast coal and the provision of mineral aggregates (MPG 3 & 6), and PPG 14 which examines the factors involved in development on unstable land, including land areas which have been subject to shallow mining.

The strategic planning framework for the study area is provided by the approved Clwyd County Structure Plan (1982a), the submitted Clwyd County Structure Plan: First Alteration (1990) and the Clwyd County Special Landscape Area Local Plan (1984). The study area is covered by the draft Alyn and Deeside (except Broughton and Higher Kinnerton) Local Plan (1984), the adopted Wrexham Maelor Local Plan (1989) and the draft Wrexham Maelor Local Plan Review (1990).



Sources of information: Wrexham Maelor Local Plan (September 1989), Draft Alyn and Deeside (except Broughton and Higher Kinnerton) Local Plan (February 1984), Clwyd County Council Special Landscape Area Local Plan (December 1984).

Figure 4 Planning factors

The general content of these plans is indicated below as a context for the subsequent discussion of geological factors which are relevant to land use planning. Since these plans are subject to review, however, some policies may be modified or changed. Therefore the reader is cautioned to check the most recent version of the plan at the local authority offices rather than rely on the account given in this report.

Both strategic and local planning strategies aim to consolidate the study area's assets and build on past successes to provide for the needs of local residents, businesses, and visitors. Emphasis is placed on improving the local economy. At the same time, older urban and industrial areas are to be regenerated and environmental quality improved. Maximum use is to be made of existing infrastructure whilst minimising the cost of new provision.

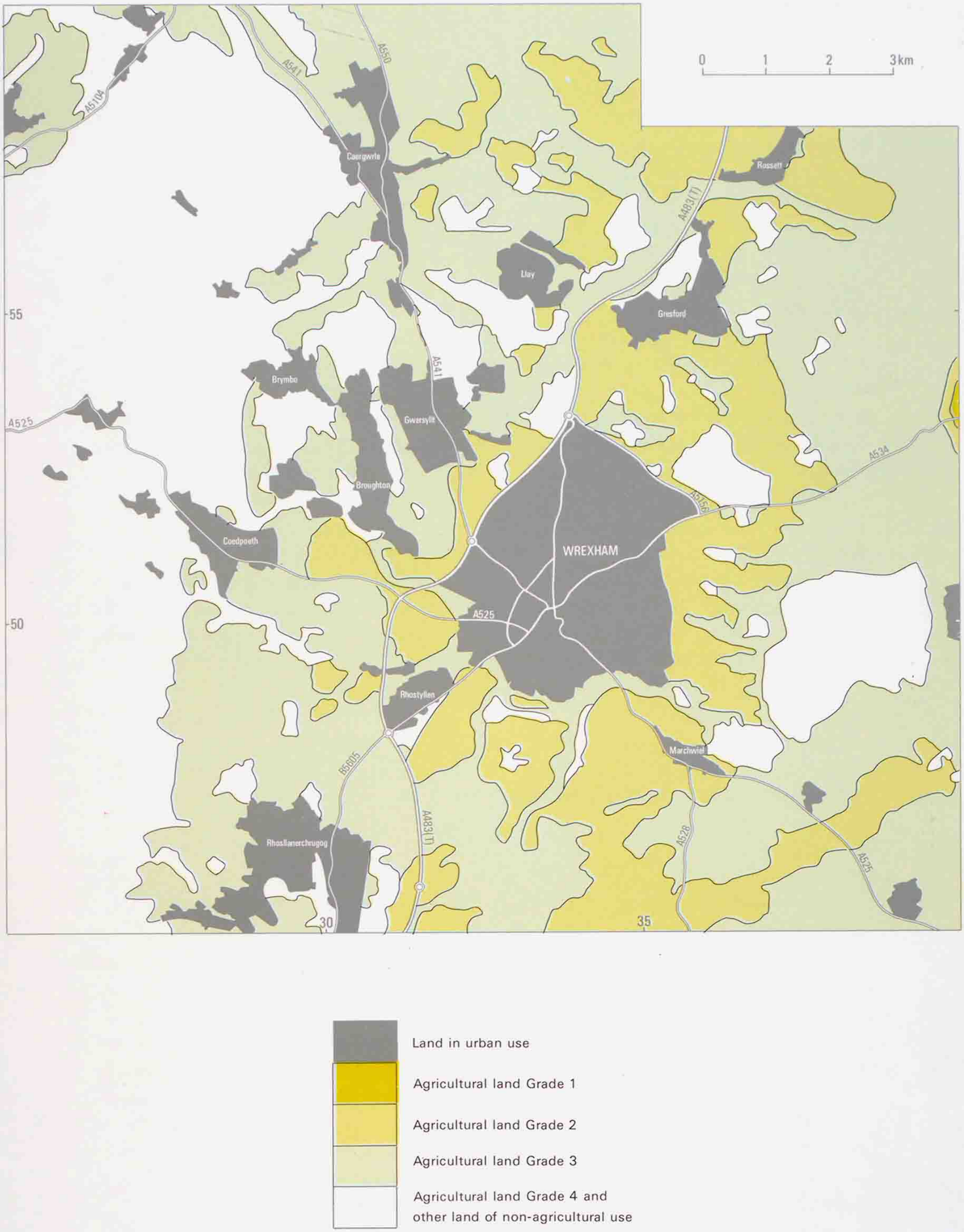
The Clwyd structure plan aims for most development to be concentrated in the existing main settlements, and indicates that the main releases of housing land in the county are to be in Wrexham Maelor. The population of Wrexham town and the surrounding 'urban villages' at the 1981 Census was close to 100,000, and continuing population growth is envisaged in and around Wrexham. While the 1982 Structure Plan placed an emphasis on growth in the 'urban villages', the Alteration, in view of the scarcity of suitable sites and related environmental considerations, indicates that a degree of expansion is to be allowed for at both Wrexham town and the outlying urban villages. The Alteration explains that over-rapid growth of Wrexham town would nonetheless be undesirable, in view of the presence of high quality agricultural land, especially to the east of the town; the presence of valuable reserves of sand and gravel; and high quality landscape to the south of the town.

The Structure Plan and Alteration also set out county-wide policies for mineral working, the protection of high quality agricultural land and protection of environmental resources.

The policies for minerals identify criteria for the consideration of proposals for mineral working and provide guidance for the safeguarding of resources and the release of land for extraction, including sand and gravel, limestone, and coal which are of particular significance in the study area.

The plan sets out a policy for Green Barriers, intended to protect the individual identity of settlements and prevent their uncontrolled expansion. In the Special Landscape Area which covers much of the higher ground of the western part of the study area, priority is to be given to the conservation and enhancement of the landscape, and in Local Landscape Areas only appropriate development will be considered. Ancient monuments, for example Offa's Dyke and Wat's Dyke, are also protected from inappropriate development as are Sites of Special Scientific Interest such as those near Minera, at Llay Bog and at Vicarage Moss, Gresford, as well as other sites of nature conservation interest. The structure plan policies are amplified and given locational expression in the local plans. Boundaries or limits to settlements are defined, to delineate the built-up areas and main sites proposed for new development, and also marking the edge of open countryside.

The major planning factors referred to in the above plans are shown diagrammatically on Figure 4. A further policy aim quoted in the structure and local plans is the protection of the best grades of



Source of Information: Sheet 109, Agricultural Land Classification of England and Wales

Figure 5 Agricultural land classification agricultural land, and is particularly significant in the vicinity of Wrexham. This factor is shown separately on Figure 5, for reasons of clarity, and the fact that the information is derived not from the structure or local plans, but the Ministry of Agriculture and Welsh Office's Agricultural Land Classification. It is to be noted that the base information used dates from the 1960's, and has been subject to partial revision; however the figure is intended to provide a diagrammatic representation of the distribution of the higher grades of agricultural land in the study area.

With respect to water resources, the National Rivers Authority controls the quality of water under the Control of Pollution Act 1974, the Public Health Act 1937 and the Water Act 1989. The Structure Plan Alteration points to the need to avoid any form of development which would cause the discharge of effluent in a manner likely to impair the quality of coastal or inland water. It follows that protection of the major aquifers of the area from, for example, industrial and toxic waste disposal is an important factor in terms of planning and development. A further environmental consideration arises from the 'Dee flood plain safeguarding areas' (Figure 4), covering those parts of the Dee valley where flooding could take place if the riverside levees were to be breached or overtopped by flood water.

In general, it is clear that consideration is required to be given to all factors affecting development costs, stability of structures, and safety. Hence, the geotechnical characteristics of deposits likely to be encountered during development need to be borne in mind, and any adverse impact related to geological features minimised. Such constraints are considered in more detail in the Summary of Geological Factors for consideration in Land-use Planning.

GEOLOGICAL BACKGROUND (THEMATIC MAPS 1-4)

Introduction

Maps 1-4 provide a background to the geology of the study area; most of the information on the subsequent Thematic Maps is derived directly or indirectly from them. A more detailed account of the geology of the area is given in Annex A. The Solid and Drift geology maps (1 and 2) are derived directly from the 1:10 000 geological maps.

The geological deposits of the area can be divided into two radically differing categories. They are, firstly, the solid (or bedrock) sediments (Figure 7), mainly mudstones, sandstones and limestones, all of which are indurated to a varying degree. They range in age from Ordovician to Permo-Triassic (some 440 to 210 million years old). Over much of the area the solid deposits are overlain by the second category, unconsolidated drift (superficial) deposits (Figure 8). These, mainly clay, stony clay, sand and gravel, form a cover of variable thickness (Figure 11) and have been deposited during the last 20,000 years.

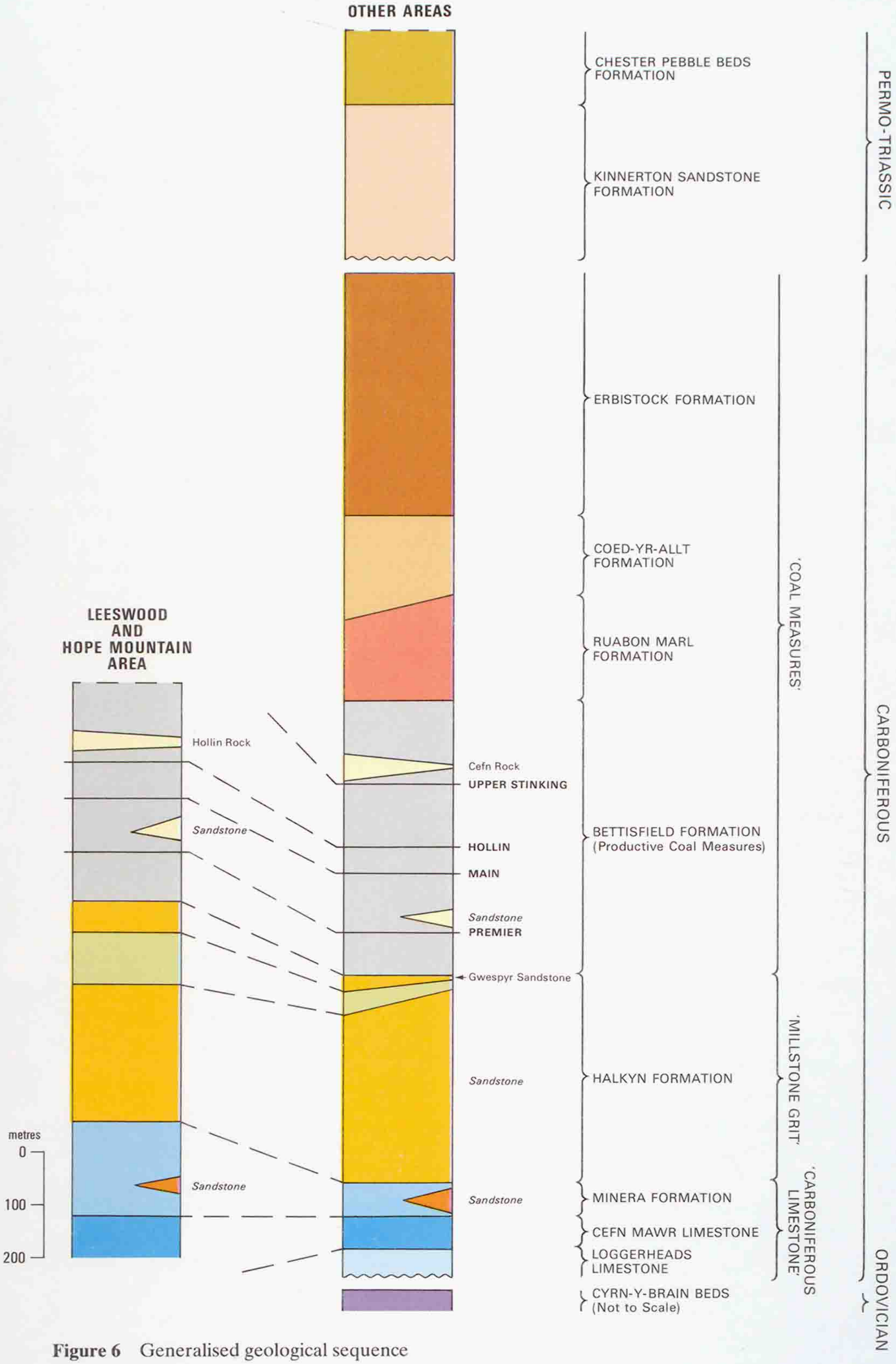


Figure 6 Generalised geological sequence

Solid geology (Thematic Map 1)

The map depicts the surface of the solid bedrock, which in many places is covered by drift deposits (Map 2), and shows the distribution of the major rock formations. It does not attempt to portray the vertical variations within the solid rock, other than in the generalised vertical section and cross-section.

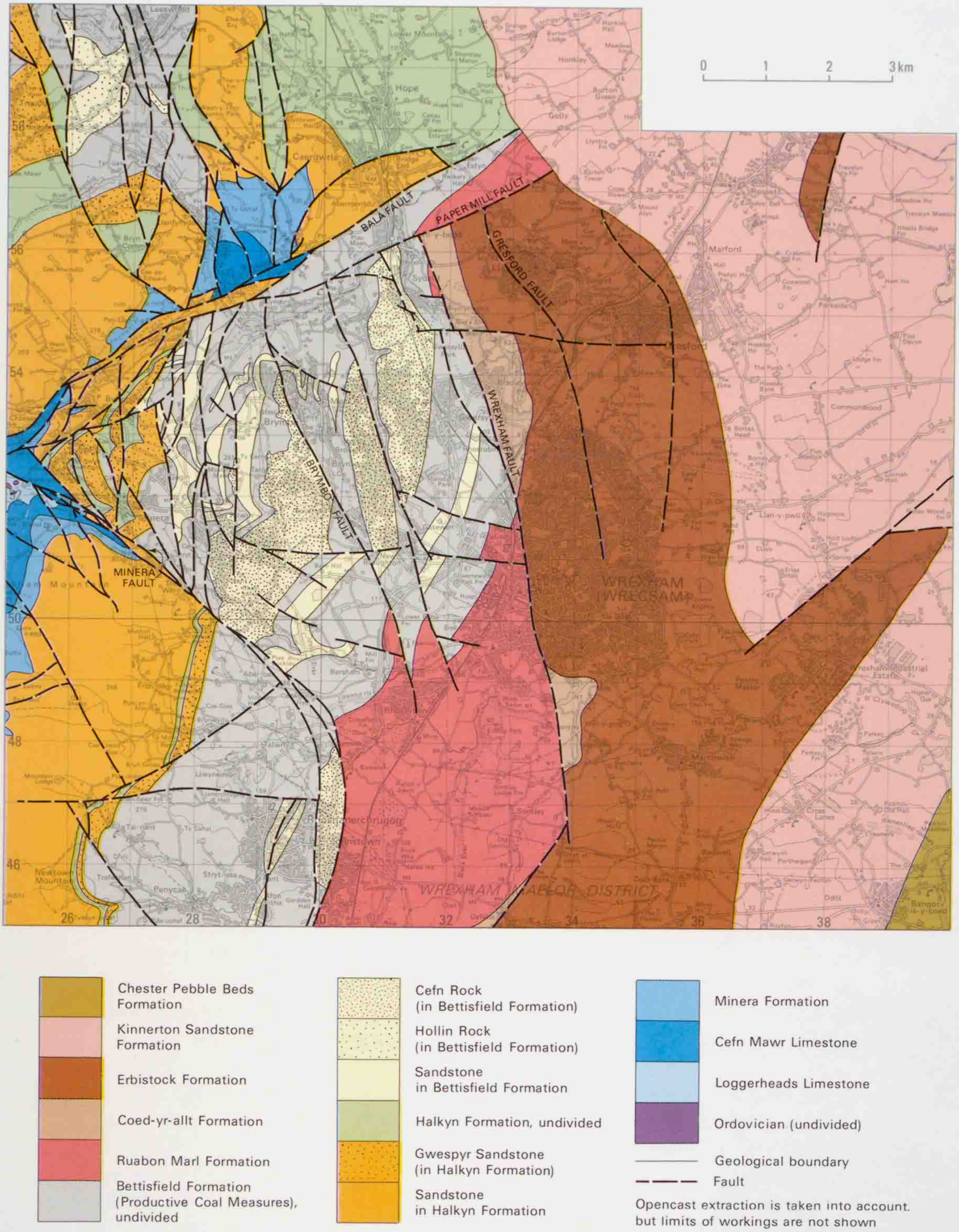
The 'formation' is the fundamental level of subdivision of a sequence of rocks and refers to a body of strata which is recognisable and mappable over large areas. The formation comprises strata of distinctive geological characteristics (e.g. similar composition, grain-size, sedimentary structures, persistent association of beds of different rocktype). Specific lithologies can commonly be recognised within a formation (e.g. sandstones, coal seams) and may be named as a 'member'. These need only be of local distribution.

The rock succession of the area is given in the form of a generalised vertical section. This shows the stratigraphic order of the formations, their thickness variations (approximately to scale) across the area and general relationships with underlying and overlying formations (i.e. normal contact or unconformity). Brief descriptions of each formation and member, including age, rocktype, lateral and vertical variations, and interpretation of mode and environment of deposition are given in the Summary of Geology (Annex A). The cross-section is an interpretation, based on available surface information and relevant borehole data, of the nature of the solid rock at depth along the line of section shown on the map. The line of cross-section was chosen to best illustrate the overall structure of the area.

This map should be used in conjunction with Map 2 (Drift geology), as the accuracy and certainty of the linework depends to a large degree on the availability of information from rock exposures and the thickness of the drift. Thus in areas of little or no drift a lesser degree of interpretation is necessary. However, in the coalfield, considerable information is available, despite a widespread drift cover, from boreholes, previous mining and opencasting. Therefore, in some areas, the position of coal seams and faults is well constrained.

Faults are discontinuities in the solid rock and may, in addition to offsetting geological boundaries, coincide with changes within the formations. Most faults in the area are steep (within 20° of vertical). No attempt is made to indicate the variation of steepness except in the cross-section. Few faults are ever seen in exposure other than in mines and quarries and, therefore, the position of most of them is inferred.

Most of the study area is underlain by sedimentary rocks of Carboniferous age. These lie unconformably on Ordovician strata, and are themselves overlain unconformably by Permo-Triassic strata. The Carboniferous sequence has, at its base, up to 225 m of Carboniferous Limestone which is mainly limestone with subordinate mudstones and sandstones. This is overlain by up to 420 m of Halkyn Formation (Millstone Grit) sandstones, siltstones, mudstones and chert. These are in turn succeeded by up to 520 m of the Bettisfield Formation (Productive Coal Measures) which is characterised by cyclic repetition of mudstone, siltstone, sandstone, seatearth and coal. The Main



This figure is a simplified portrayal of 1:25 000 scale map 1 which should be consulted for detailed information

Figure 7 Solid geology

coal locally exceeds 4 m in thickness and a number of other coals are more than 3 m thick in places. The Productive Coal Measures are succeeded by up to about 900 m of 'Red Measures' (Upper Coal Measures). These also commonly show a cyclic repetition of strata, but coal seams are poorly developed. The succeeding Permo-Triassic sandstones (up to 540 m) are entirely covered by thick drift deposits, of glacial or post-glacial origin, as is most of the outcrop of the Productive Coal Measures and 'Red Measures'.

The most significant structural feature is the ENE-trending Bala fault system (Figure 7). It has a long and complex history, possibly since Precambrian times, and there are significant differences in the Carboniferous sequences on either side of it (Annex A). It does not affect the Permo-Triassic rocks, although it can be traced by geophysical methods for some distance under the unconformable Permo-Triassic cover.

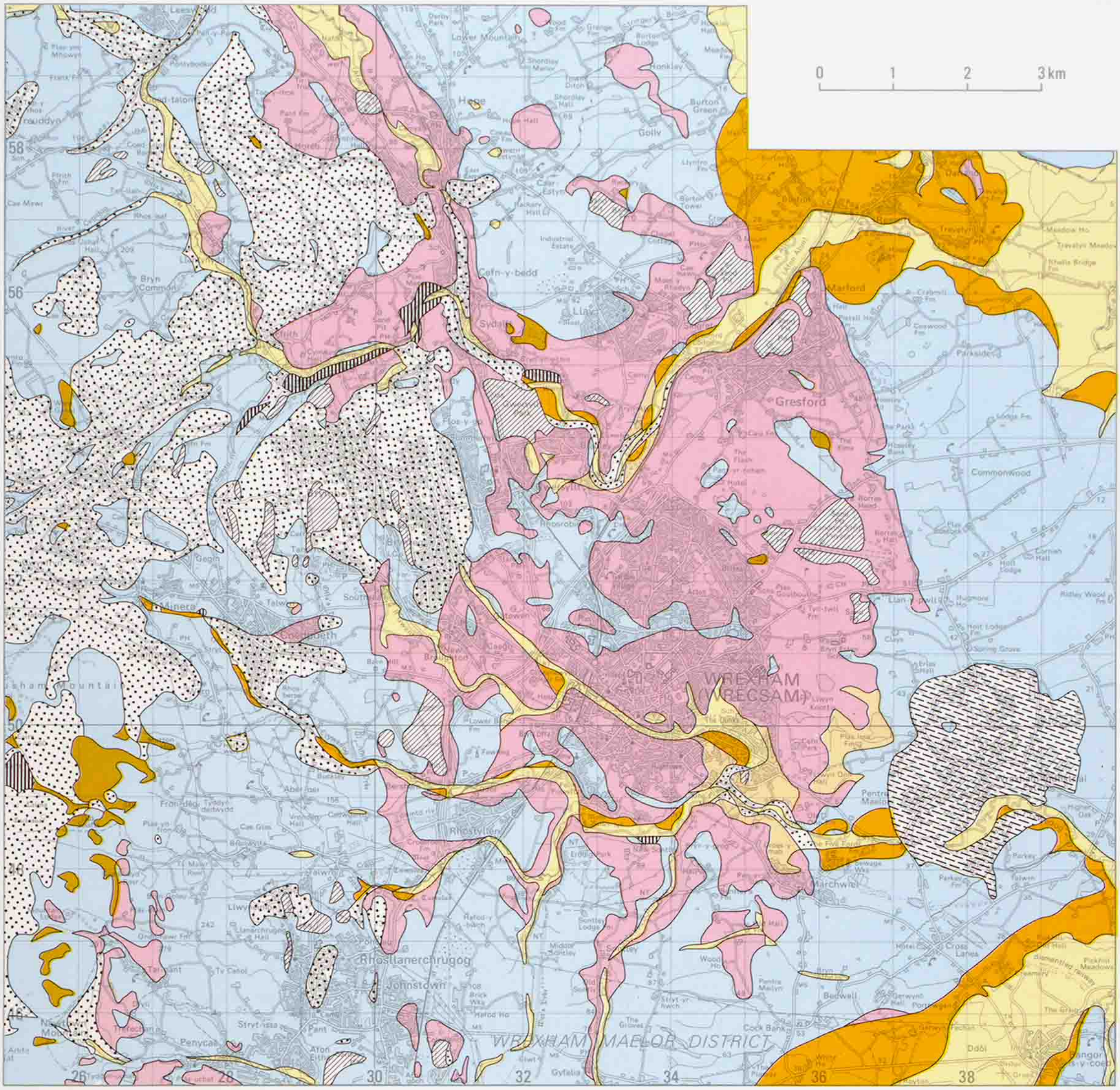
On the southern side of the fault system the strata have a general gentle dip towards the east (see Horizontal Section), and in broad terms this is reflected in the topography. There are a number of major NNW-trending faults (such as the Gresford and Wrexham faults) with a subsidiary E-W-trending set. To the north of the fault system the structure is more complex. Lead, zinc and copper mineralisation is largely confined to the Minera area, to the south of the Bala fault system. This mineralisation occurs mainly as discontinuous veins along NW-SE-trending faults and joints, and in some steep pipes.

Drift geology (Thematic Map 2)

This map shows the distribution at surface of all drift (superficial) deposits. The general term 'drift' is applied to the unconsolidated, superficial deposits of the most recent (Quaternary) age, and these are largely glacial in origin or are related in some way to the glacial period which ended some 10,000 years ago. Localised peat and clay-filled depressions related to the deglaciation, and known as kettle holes, are symbolised. Deposits which have formed recently, or are actively forming by natural processes are also shown, together with man-made deposits (made ground, backfill and landscaped ground). The map also displays landslips of various ages (Quaternary to Recent).

The drift and other unconsolidated deposits are categorised according to two factors, a) the process by which they were formed, and b) the composition of the deposit. The former includes landslip, made ground, backfill, landscaped ground and the various forms of alluvium. The latter includes till (boulder clay), sand and gravel, glaciolacustrine deposits and peat. Those categorised solely according to process are therefore very variable in grain-size, clast content and fabric.

The map shows only the variation of surface deposits (i.e. within 1 metre of surface) and makes no attempt to show variations with depth. Although the deposit indicated on the map may be considerably thicker than 1 metre and perhaps the only deposit overlying the solid rock at a given site, it is equally likely that there may be many different types of deposits. Therefore, borehole data must be consulted (Annex D). Drift thickness variations are shown on Map 4, and further information in the Summary of Geology (Annex A).



- Landslip
- Peat
- Alluvium
- River Terrace Deposits, undifferentiated
- Glacial Sand and Gravel
- Glaciolacustrine Deposits
- Till (Boulder Clay)
- Solid rock at surface
- Worked out opencast coal area
- Worked clay or sand and gravel pit, wholly or partially backfilled
- Landscaped ground (Wrexham Industrial Estate)

Areas of made ground omitted for clarity

This figure is a simplified portrayal of 1:25 000 scale map 2 which should be consulted for detailed information

Figure 8 Drift geology

Deposits generally less than 1 metre thick are not shown. Areas shown as solid rock (bedrock) may have extensive veneers of drift. It may locally exceed 1 metre in thickness, but such areas are too patchy to show. Thin drift veneers may, however, be a very important factor when considering local ground stability (Waine et al., 1990). Much of this veneer would be classified as 'head', a product of weathering commonly combined with solifluction and hill-creep. Head has not been shown as a separate deposit on the geological maps or on this Thematic Map; where it is of appreciable thickness it is included with alluvial or glacial deposits.

The categories of drift and other unconsolidated deposits are briefly reviewed below.

Landslip

There are landslips in both bedrock and superficial deposits. Some of these landslips are still active [e.g. SJ 3260 4844]. Most of the landslips recognised are probably of immediate post-glacial age and may not have been active for thousands of years. It must be stressed, however, that excavation or loading of recorded landslips, and particularly the fronts of landslips, is likely to reactivate them. Most landslips occur along steep-sided valleys, and are particularly common where the Halkyn Formation or Coal Measures are the bedrock, or where there are thick drift deposits. In such valleys landslips may be reactivated or triggered by active stream erosion. Even where a landslip has not been mapped it should be emphasised that any of these steep valley sides are potentially unstable. Examples of landslipping are along the valleys of the R. Cegidog [SJ 288 548 - 308 550] and R. Alyn [SJ 323 549].

Made Ground

Most areas of made ground are related to mining (metalliferous and coal), quarrying, land development and road and railway embankments. The largest areas are those associated with the Minera lead mines [around SJ 261 519 - 277 509], Brymbo Steelworks [SJ 298 534], the deeper coal mines in the eastern part of the coalfield for example at Llay Main Colliery [SJ 325 562], Bersham Colliery [SJ 312 480], Hafod Colliery [SJ 311 469] and Gresford Colliery [SJ 336 538], and along the A 483 trunk road. Most made ground is only up to a few metres thick, but tips associated with the deeper coal mines may exceed 35 m in height. On the map a distinction is made between made ground related to mining activities and other made ground; further information is given on Map 5 (Mining activities - Coal/Metalliferous), Map 6 (Bedrock resources - except Coal/Metalliferous) and Map 7 (Sand and gravel resources).

Metalliferous mining waste tips generally comprise calcite vein material and the local country rock, principally limestone. Some of the tips, however, may contain a significant content of sulphide minerals (galena (lead) and sphalerite (zinc)). Coal mining tips usually comprise mudstone, siltstone and sandstone debris, and sometimes have an appreciable content of coal. Some of the larger tips (e.g. Llay Main) are gradually being removed or landscaped and their contents used for the manufacture of breeze blocks and similar products. Made ground related to limestone quarrying generally comprises calcareous mudstone and muddy limestone, while that related to sand and gravel extraction usually consists of fine-grained sand, silts and mud.

Backfill

Backfill of sand and gravel, opencast coal and other extraction sites usually comprises the waste products of the extraction (e.g. sand and gravel [SJ 357 560], coal [SJ 307 499], clay [SJ 309 454]) as given for made ground above. It may also include, however, household rubbish and industrial waste at approved sites (Figure 18). On the map a distinction is made between backfilled opencast coal sites and other types of backfill.

Landscaped ground

Landscaped ground refers to areas where the original topography has been extensively remodelled by earth-moving and tipping and where it is impracticable or impossible to delineate areas of made ground. In the present study its use has been restricted to the Wrexham Industrial Estate where most of the land falls into this category. Most of the area of the estate was originally a military establishment with installations both above and below ground; these have mostly been demolished and the area landscaped for industrial use. Further landscaping is commonly undertaken as industrial development takes place.

Alluvium

Alluvium (floodplain deposits) occurs along most of the more important streams and rivers. It occupies a considerable area along the Dee valley both in the south-eastern corner of the study area near Bangor-is-y-coed and in the north-east around Trevalyn Meadows. There are significant stretches of alluvium along the Alyn valley upstream from Caergwrle and downstream from Gresford. Alluvium is still actively forming alongside many streams and rivers as a result of periodic flooding. It consists mainly of fine sands, silts and clays, with local gravels; commonly sands and gravels in the lower part of an alluvial deposit are overlain by silts and clays above (see also Map 7 – Sand and gravel resources).

Alluvial Fan deposits are of limited extent and have been included with alluvium on Map 2. They are shown separately on the 1:10 000 geological maps. They form where constricted streams and rivers flow into a less constrained area (e.g. the alluvial floodplain of a large river) and the sediment carried by the stream is laid down in a deposit which increases areally downstream. There may be a pronounced grain-size decrease downstream on the fan (e.g. gravel varying downstream to fine sand and silt).

Alluvial Terrace

Alluvial terraces are best developed in the southeastern and northeastern parts of the area, adjoining the alluvium of the River Dee and the lower reaches of the River Alyn. Elsewhere they are localised and of small scale. They comprise similar material to other alluvium, though commonly with a higher sand and gravel content. They represent flooding during formerly higher levels of the stream or river (see also Map 7 – Sand and gravel resources).

Lacustrine Alluvium

These deposits are very limited in extent, occurring only in a few kettle holes in moundy sand and gravel terrain. They were laid down in small temporary lakes and ponds from post-glacial to recent times. They are not distinguished from alluvium on the Thematic Map.

Till (Boulder Clay)

This is a very widespread deposit. It largely covers a broad tract from Bersham and Minera southwards to the southern margin of the study area, and thence eastwards to the Dee valley and north through the Wrexham Industrial Estate to the Alyn valley. It also covers a large area between Hope and Burton, and blankets much of the Leeswood Coalfield. It is extremely variable in composition and was the product of direct deposition from melting glaciers. Clasts of varying size up to several metres are suspended in a clay matrix. There is usually no order or bedding though occasional beds of sand, gravel and silt may be intercalated.

In the area, there were two different sources of boulder clay, with quite different suites of clasts, clay matrices and grain-size characteristics (see Summary of Geology (Annex A) for further details).

Glaciolacustrine Deposits

These deposits occur beneath glacial sand and gravel to the south-east and east of Wrexham and adjacent to the Wrexham Industrial Estate. They are also seen in the sides of the Alyn valley between Bradley and Gresford. They comprise bedded silts and very fine sands and were laid down in an ice-dammed glacial lake (see Annex A). They are difficult to differentiate in the field from other glacial deposits and are probably more extensive than indicated on the map (see Map 9, Engineering geology – drift).

Peat

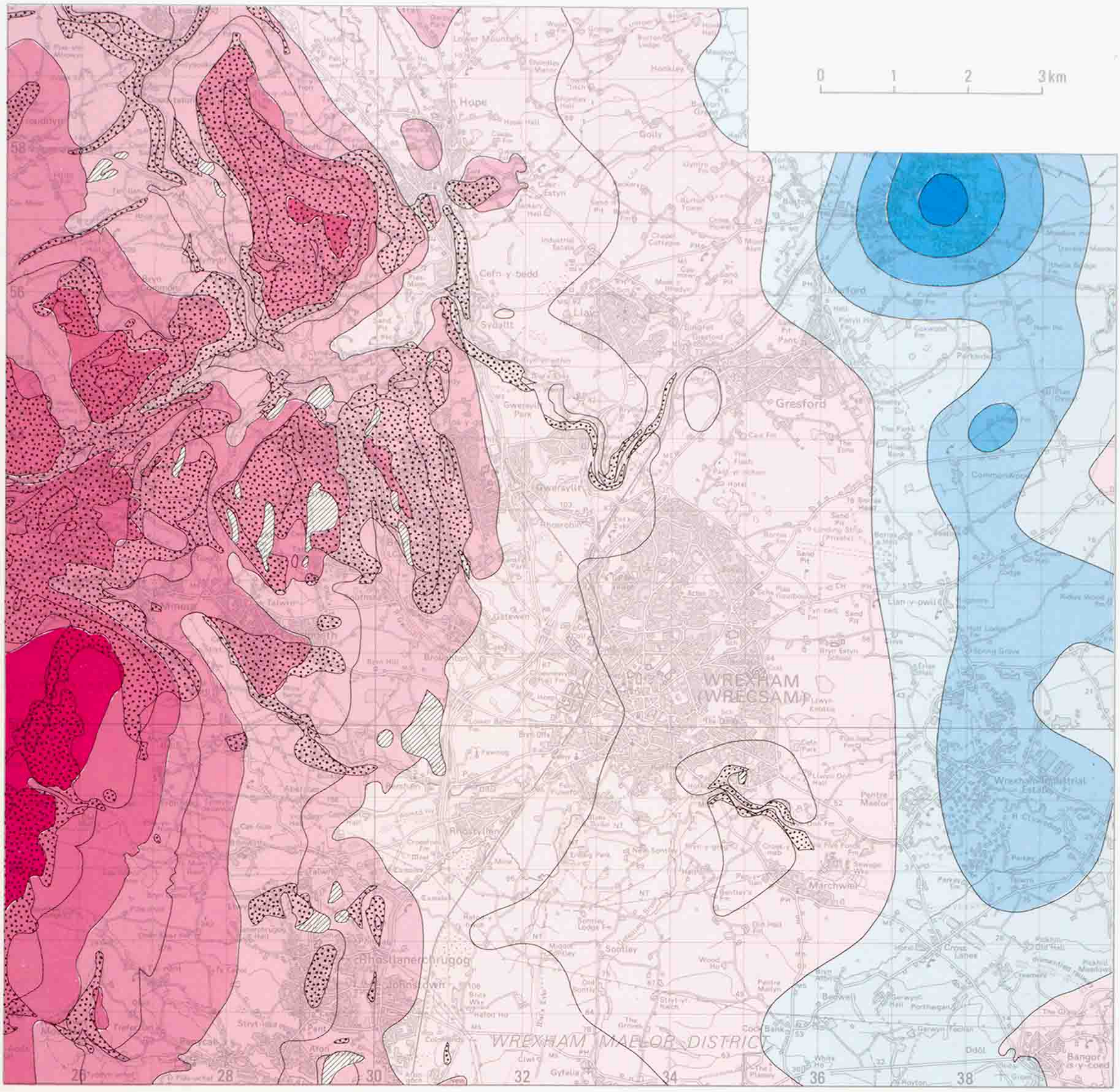
Hill peat (generally less than 2 m thick) is present on the eastern slopes of Esclusham Mountain, west of Fron-deg. Small areas of thicker peat occur in some kettle holes.

Rockhead elevation (Thematic Map 3)

Rockhead elevation is the height relative to Ordnance Datum of the surface of the bedrock. Thus the rockhead elevation contours, as shown on this map, are contours on the topographic surface which would be revealed if all drift (superficial) deposits were stripped off. It follows that in areas where bedrock is at or very close to the ground surface (shown by a grey stipple on the map) the rockhead contours and present-day topographic contours will be coincident. Figure 9 displays a simplified version of the contours.

There are sometimes problems in defining the exact height of the rockhead where the bedrock has an appreciable zone of weathering. This is most noticeable in the mudstones of the Halkyn and Bettisfield formations where the weathered zone may be several metres thick.

The rockhead elevation contours have been computer generated (Loudon et al., 1991) from two main sources. Chief of these is the borehole database (Annex D), and both confidential and non-confidential boreholes have been used in their compilation. Information comes from those boreholes which have a reliable depth for the rockhead, and from those which fail to reach bedrock but nevertheless provide a maximum height for the rockhead. Additionally the contours are constrained by the coincidence of the drift margins with the topography. Borehole evidence and



500	0
450	-20
400	-40
350	-60
300	-80
250	-100
200	
150	
100	
50	
0	

Metres relative to O D

The contours relate to natural rockhead surface only

Solid rock at surface

Worked out and backfilled opencast coal pit

This figure is a simplified portrayal of 1:25 000 scale map 3 which should be consulted for detailed information

Figure 9 Rockhead elevation

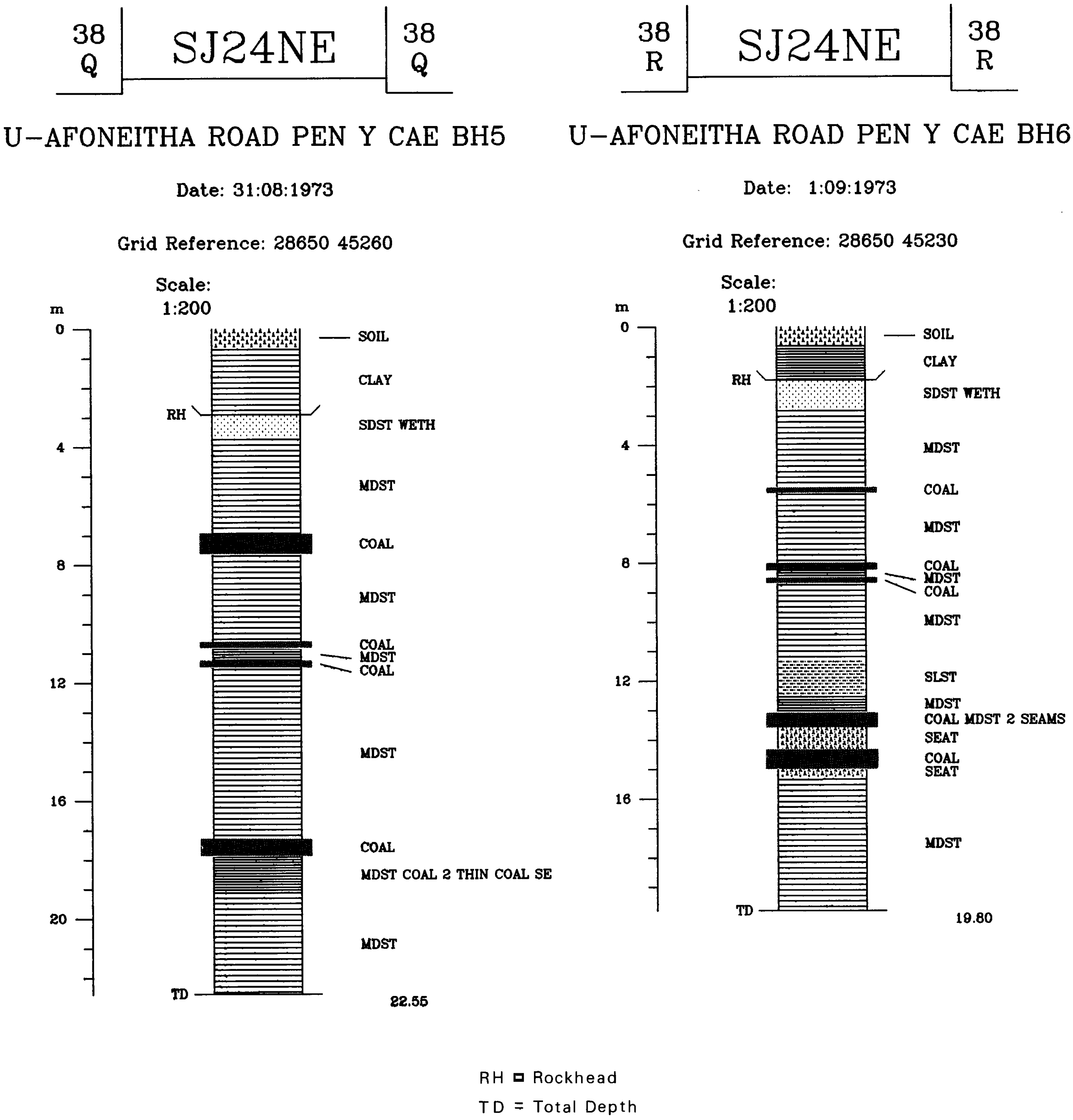


Figure 10 Examples of computer-derived graphic borehole logs

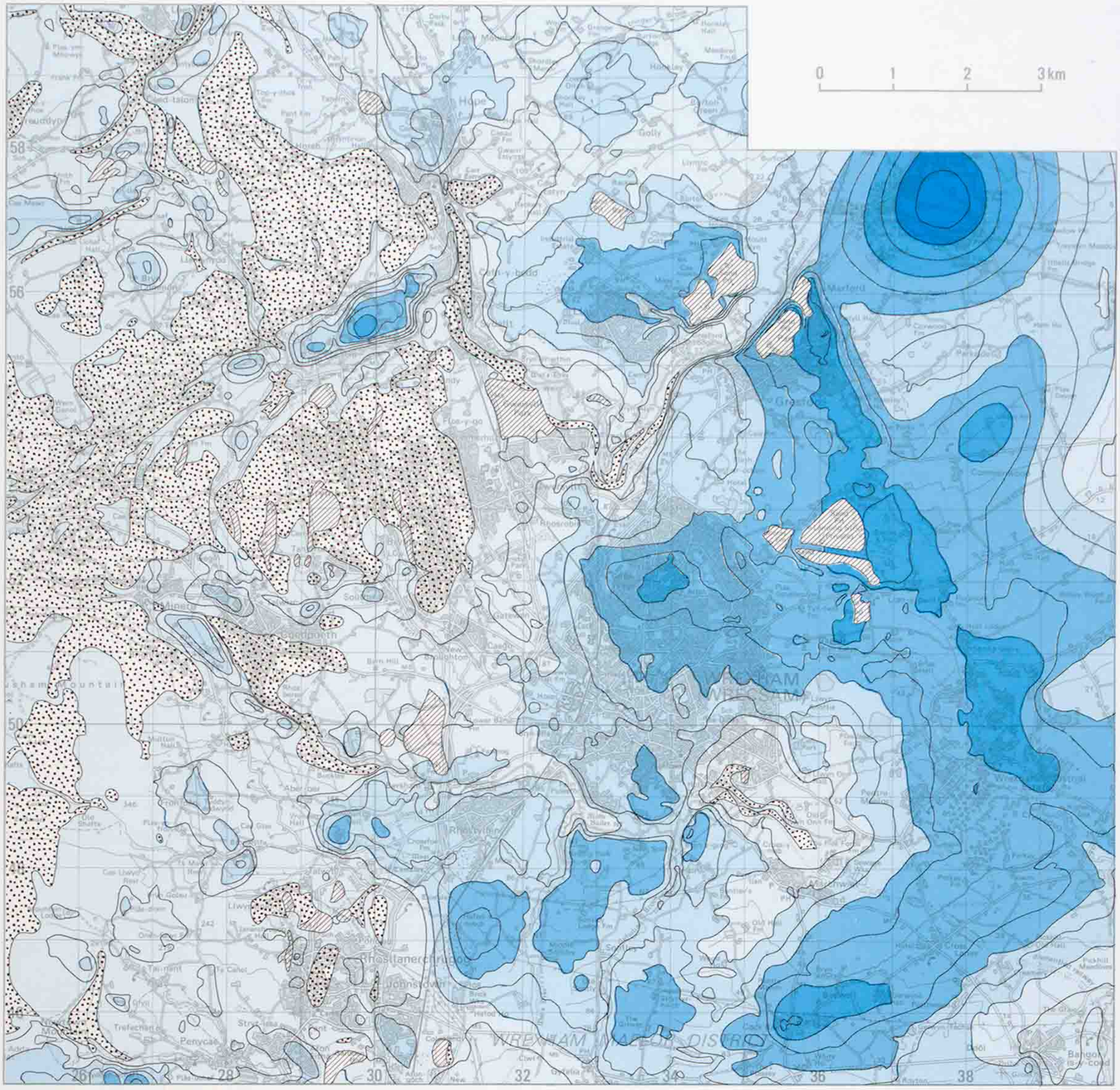
outcrop information from a 2 km wide strip outside the margin of the study area was also used in order to define more closely the rockhead elevation near the margin. Borehole sites, for reasons of confidentiality, have not been shown on the map; however, to give an impression of the reliability of the contours an inset map of borehole density has been provided. As well as producing rockhead elevation contours the borehole database can be used to generate graphic vertical sections (Figure 10), three-dimensional diagrams and other plots.

The form of the rockhead contours particularly indicates the form of buried channels related to the major river systems and elsewhere. In the eastern part of the area the rockhead contours show a steady eastward slope towards the buried valley of the pre-glacial River Dee. Borehole control is poor in this area, especially since few boreholes reach bedrock, but information from the study area and surrounding areas indicates that, in its northern part, the pre-glacial Dee valley had a NNW trend approximately through Ridleywood [SJ 399 518] and Trevalyn [SJ 380 567], with its base well below Ordnance Datum. Local smaller scale sub-drift, and in many cases sub-glacial, channelling is seen in a number of places, notably west of Rhosllanerchrugog and adjacent to the restored Plas Power opencast coal site.

Drift thickness (Thematic Map 4)

The drift thickness contours, or drift isopachytes (simplified in Figure 11) were obtained by interacting the rockhead elevation contours with the Digital Terrain Model (DTM). The DTM is a digital record of the topographic contours of the area. The thickness of drift at any point is the difference in elevation between the topographic surface and the rockhead surface and a contoured map of drift thickness can be obtained by subtracting the heights given by the rockhead elevation plot from those of the DTM (details of this process are given in Loudon et al., 1991). They also emphasise the general increase in drift thickness towards the east of the area, but additionally they highlight the considerable local variation within this general trend.

A knowledge of the approximate rockhead height and the drift thickness is of great value when planning site investigations. Maps 3 and 4 can be used in conjunction with Map 2 (Drift geology) and Map 9 (Engineering geology – drift), and the information contained within the Borehole Database (Annex D), to obtain a preliminary assessment of ground conditions.



Solid rock at surface

0
10
20
30
40
50
60
70
80
90
100

Metres relative to O D

The contours relate to drift deposits only and do not take into account made ground

Worked out opencast coal, sand and gravel pits; other backfilled areas (not all sand and gravel pits are backfilled)

This figure is a simplified portrayal of 1:25 000 scale map 4 which should be consulted for detailed information

Figure 11 Drift thickness

MINING AND MINERAL RESOURCES (THEMATIC MAPS 5-7)

Mining activities – Coal/Metalliferous (Thematic Map 5, and Figure 12)

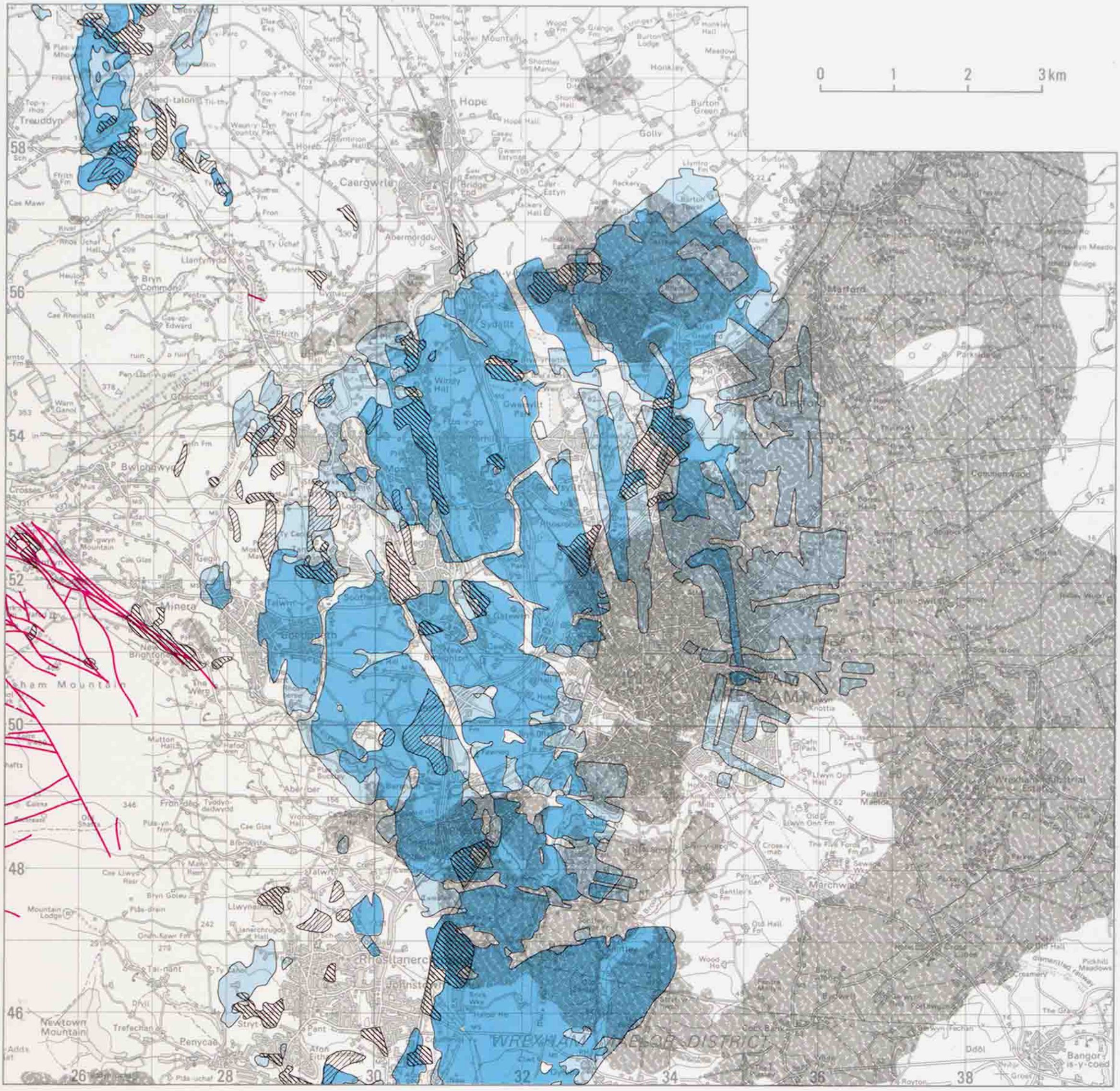
This map shows the areas mined for coal and metalliferous ore, and aspects related to that mining. Some of the early mines were sunk for iron ore (siderite) rather than coal, and some specifically for the extraction of fireclay (seatearth). The information on coal mining is derived to a large extent from that of the British Coal database (Opencast Executive, Coal Commission and other abandoned mine plans) and BGS archival data. The information on metalliferous mining is derived from previous surveys of the area with supplementary BGS archival plans and maps. The map gives a broad picture of where undermining has, or may have, taken place, and consequently gives an indication of areas where land instability may occur. In the case of specific site investigations, the documents held by British Coal and at the Aberystwyth Office of the BGS should be consulted.

Coal Mining

Coal has been mined in the area at least since the Middle Ages and possibly earlier. Earliest workings were likely to have been of coal at outcrop in the western part of the coalfield, gradually developing into shallow workings by adits and bell pits. The concentration of shafts related to shallow workings around Rhosllanerchrugog is particularly striking. With the advent of greater demand for coal during the industrial revolution, deeper mining became prevalent and steadily extended eastwards under an increasing cover of 'red measures' (Ruabon Marl and higher beds). The deepest workings, at the eastern edge of the worked area, reached depths of more than 1000 m below OD. Deep mining in the area ceased with the closure of Bersham Colliery in 1987.

The map delimits the areas of underground workings for which plans are available. Prior to 1872, there was no statutory obligation to record plans of underground workings. The only information relating to very early mining derives from surface expressions (e.g. shafts, depressions, waste tips) where recognisable. Even after 1872, the plans lodged with the Mines Record Office (copies of which are held by British Coal) were of very variable quality and accuracy. Few of the older plans record details of depth of workings and many show little surface detail by which they can be positioned. On some plans, for example, it is clear that the direction of north shown is inaccurate, and plotting such information is therefore liable to considerable error. Plans for the more recent deep mining in the eastern part of the coalfield (e.g. at Bersham Colliery) are detailed and accurate.

The areas of underground workings shown are differentiated into areas where only one coal seam has been worked and those where more than one seam has been worked. Approximately 60 km of the area is known to be undermined. No attempt is made to indicate the depths of workings since insufficient information is available for much of the area. It is certain that the records of underground workings are incomplete. Thus, known mine-shafts, adits and coal waste tips are shown in areas without any mine plans. The possibility exists, therefore, of shallow workings anywhere in the area where the Bettisfield Formation (Productive Coal Measures) is at or near surface (Map 10) and particularly so where the thicker seams (e.g. the Main and Quaker coals) occur at outcrop or shallow depth. The likelihood of shallow workings will decrease with increased superficial overburden.



Areas of underground working for coal, where at least one seam has been worked

Areas of underground working for coal, where more than one seam has been worked

Made ground: man-made deposits related to mining

Worked out and backfilled opencast coal pits

Lead, and subordinate zinc and copper, veins

Approximate areas with more than 30m of drift cover

Mine shafts and adits are not shown (see map 5)

This figure is a simplified portrayal of 1:25 000 scale map 5 which should be consulted for detailed information

Figure 12 Mining activities

Many of the mine-shafts and adits shown were recorded during the various surveys of the area. Additional sites have been transferred from British Coal plans (which indicate the validation of the data) and all have been checked against the British Coal Shaft Register. Even so, the exact sites of many of the shafts shown are uncertain. Some 1350 shafts and adits are recorded, but unrecorded shafts are likely to exist. Some shafts have been treated by capping or filling. However, it cannot be assumed that treatment carried out in the past remains effective, or that it was undertaken to standards suitable for future specific land uses. Uncapped shafts may be wholly or partly filled. Therefore all shafts need to be located, their condition determined, and any necessary precautionary works undertaken before development of the land.

It cannot be stressed too strongly that shallow workings, shafts and underground workings may exist in addition to those shown on the map, and that the limits of underground workings are only approximate. Unrecorded shafts, in particular, are a hazard and are liable to collapse without warning.

There is little site-specific information about the methods of underground working used in the older mines. However, it is known that two general methods were employed. The earliest technique of large-scale extraction was the 'pillar and stall' method. This involved the selective extraction of coal, leaving up to 60% in position to support the roof of the seam. Subsequent improvements in technique increased the efficiency of recovery. Thus panel working and longwall methods were used from the latter part of the 19th Century onwards (and probably applied in some cases to seams already mined by pillar and stall). Many of the available mine plans suggest longwall extraction was used. This involved the complete removal of coal from certain areas resulting in the controlled collapse of the unsupported seam roof. On the map, no attempt is made to show areas of potential subsidence due to mining. This would relate to the age and depth of workings, and number of worked seams and the thickness of superficial deposits. However, the map does show areas where the drift cover is greater than 30 m thick since, in general, the effects of collapse of old workings are largely masked by overburden of that thickness.

Of the two main methods of mining, areas of pillar and stall provide the greater potential hazard to development. As a large proportion of the seam was left as roof support, a borehole is highly likely to pass through the pillars (i.e. the preserved seam) rather than adjacent voids. Furthermore, downward bowing of the seam roof between pillars may suggest in a borehole that only a thin seam is present, whereas voids close to the pillars may still exist. Collapse of the pillars themselves can result in cavities, breccia pipes and voids in overlying strata. In most parts of the coalfield any voids are now likely to be filled with water.

Longwall extraction, used generally for the deeper seams, typically results in the collapse of the unsupported seam roof during or soon after mining and further collapse is unlikely. Only the connecting 'roads' which were permanently supported for access are likely to cause later subsidence problems and problems with voids. Most of these workings in the western part of the coalfield (i.e. where the Bettisfield Formation is at surface or crops beneath drift) had been abandoned by the 1930's and consequently little subsidence due to collapse is likely. Recent mining has been confined to the deeper part of the coalfield to the east, under a thick overburden of 'red measures' and drift,

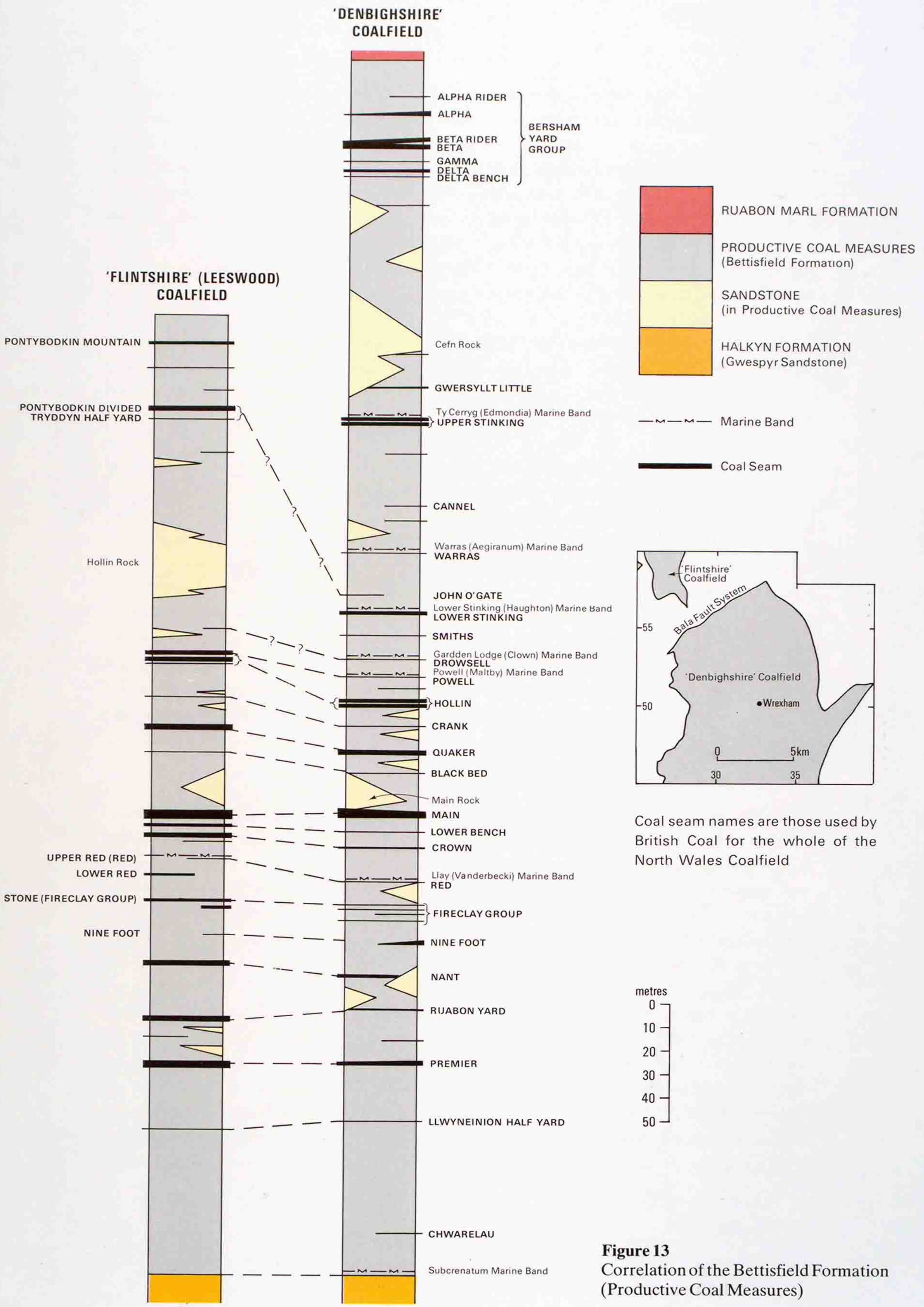


Figure 13
Correlation of the Bettisfield Formation (Productive Coal Measures)

at collieries such as Bersham and Gresford. Here the depth of the workings, added to the diffusing effect of the drift, mask any subsidence.

The most extensively worked seams are the Main and Quaker coals (see Summary of Geology, Annex A). The total area with Bettisfield Formation (Productive Coal Measures) at surface or at crop under drift is about 50 km. Under the 'red measures' the worked area extends to a further 45 km. The cumulative average thickness of all the coal seams is some 20-25 m. The original 'resources' of the area were of the order of 1300,000,000 tonnes. Of this total, the extent of recorded workings suggests that approximately 30-40% of these resources have been substantially extracted. The remaining 'resources' are not necessarily readily available (e.g. due to unrecorded mine workings, substantial overburden, local thinning and washouts of coal seams), or amenable to modern extraction methods. Furthermore, no attempt can be made to assess the quality of individual seams. As coal seam nomenclature varies across the area, a 'correlation' of the local seam names with the name used by British Coal for the whole of the North Wales Coalfields is given in Table 1.

Backfilled opencast sites are shown, as are areas of made ground (waste tips) related to coal mining. Only one opencast site is active at present, at Cae-llo; recent opencasting near Llay Hall [SJ 316 549] was completed in 1989 and is now backfilled and restored.

Iron Ore

Iron ore in the form of nodules and, less commonly, thin layers of siderite (impure iron carbonate) is widespread throughout the Bettisfield Formation. It was worked extensively in the 19th Century at such places as Brymbo and Ponciau, generally in conjunction with the mining of coal (Wedd, Smith and Wills, 1928). The industry has been extinct for many years though the steelworks at Brymbo continued in production until 1990.

Fireclay

Fireclays, mainly as seatearths to coal seams, occur throughout the Bettisfield Formation. Several have been worked in the past for refractory materials (Geological Survey of Great Britain, 1920b) the main locations being at Llay Hall Brickworks [SJ 318 551] and Cae-llo Brickworks (Smelt Pit) [SJ 288 543].

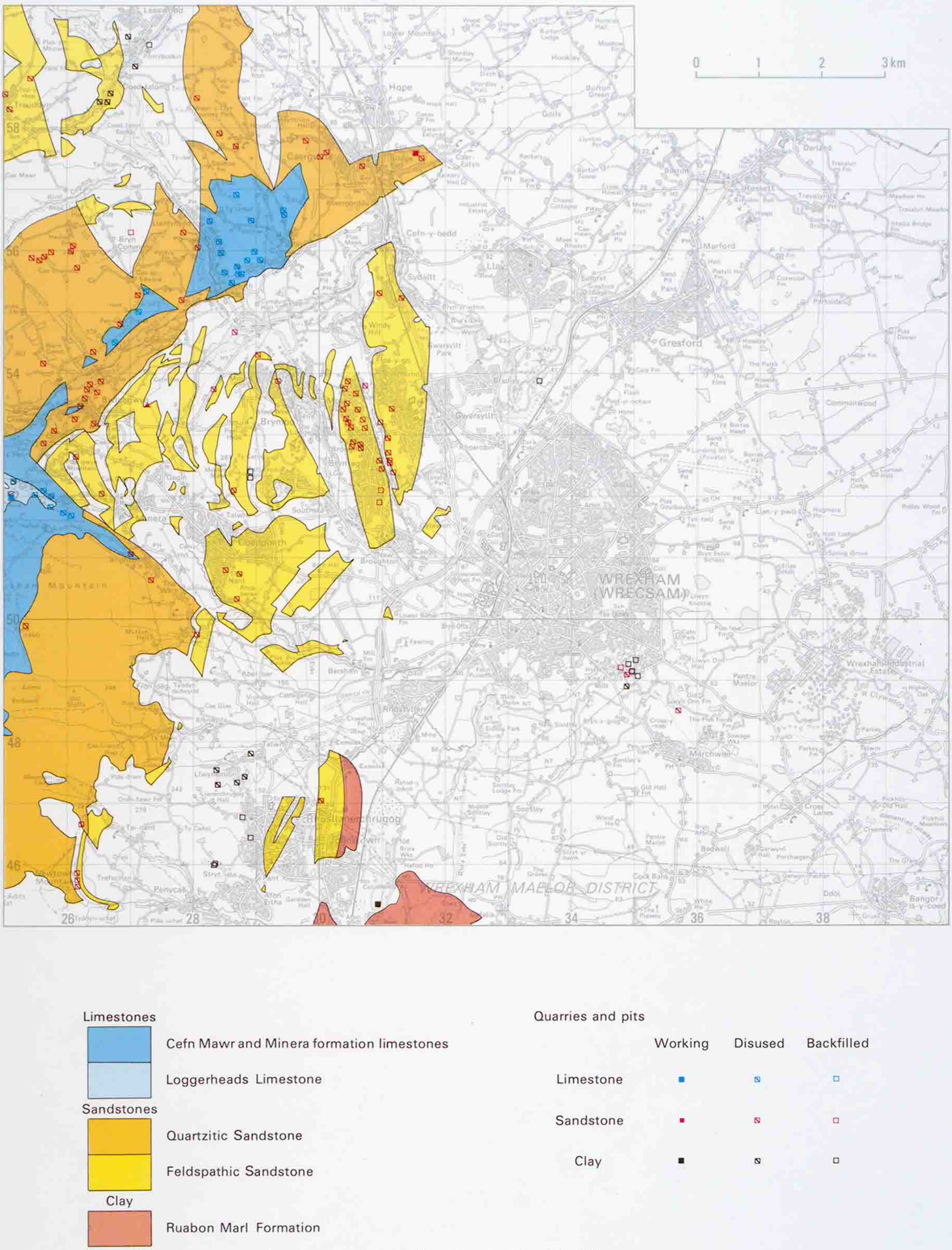
Metalliferous Mining

Metalliferous mining was restricted to the west of the area around Minera and was largely concentrated on the upper geological formations of the Carboniferous Limestone (see Summary of Geology, Annex A – Mineralisation). The lead ore galena was the main economic basis for the industry with most production between 1855 and 1880 and a minor revival in 1900 (Smith, 1921; Earp, 1958). Silver extracted from the galena was a valuable by-product. The zinc ore sphalerite was not mined in appreciable quantities until 1865, with most production concentrated between 1880 and 1895. Mining had effectively ceased by 1920. As little of this mining was recorded, no attempt is made to show areas of underground working. Unlike coal mining, however, the areas of mining were mostly restricted to narrow, relatively thin veins and joints which tend to occur in conjugate sets. As these veins can, in many instances, be well defined by the linear chains of shafts

Table 1 'Correlation' of Coal Seam nomenclature for the Leeswood and Wrexham areas of the North Wales Coalfield, after British Coal

Whole Coalfield Name	Local names: Leeswood Coalfield	Local names: Wrexham area of 'Denbighshire Coalfield'
Alpha Rider to Delta Bench	—	Alpha Rider to Delta Bench } Bersham Yard Group
Gwersyllt Little	—	Gwersyllt Little or Little
Upper Stinking	—	Upper Stinking, Top Droughy, Cefn, Droughy or Top Four Foot
Cannel	—	Cannel
Pontybodkin Mountain	Pontybodkin Mountain, Mountain or Top	—
Warras	—	Warrras, New or Ribbon
John O' Gate	Pontybodkin Divided, Divided or Mountain; Tryddyn Half Yard or Half Yard	John O' Gate, Sulphur, King or Thomas Evans
Lower Stinking	—	Lower Stinking, Bottom Droughy, Droughy, Yard, Four Foot or John The Gate
Smiths	—	Smiths or Top Yard
Drowsell	—	Drowsell, New Century or Crown (bottom leaf only)
Powell	Powell	Powell or Yard
Hollin	Hollin, Two Yard or Little (bottom leaf only)	Hollin, Two Yard, King or Seven Foot; Two Yard Bench (bottom leaf)
Crank	Crank	Crank or Yard
Quaker	Brassey	Quaker, Brassey, Brass Vein, Five Foot or Four Foot
Black Bed	Rough, Black Band or Black	Black Bed, Pin, Pin and Shale or Black Vein
Main Bind	Main Bind	Main Bind
Main	Main	Main
Main Bench	Main Bench or Little	Main Bench
Lower Bench	Lower Bench, Two Foot or Finger	Pin, Little, Brassey or Crown
Crown	Diamond, Five Foot Six, Four Foot or Jubilee	Crown, Yard, Upper Yard, Little, Crank or New
Upper Red	King	Upper Red, Red or Crank
Lower Red	Cannel, Two Foot Six, Three Foot, Stinking or Little	Lower Red, Red, Two Foot or Stone
Stone	Stone, Five Foot or Four Foot	Stone, New, Top Fireclay, Fireclay, Cannel, Middle Stone or Half Yard } Fireclay Group
Half Yard	—	Half Yard, Bind, Bench, New or Strange } Fireclay Group
Fire Damp	—	Fire Damp, Bench, Stone, Nant } Fireclay Group

Whole Coalfield Name	Local names	
	Leeswood Coalfield	Wrexham area of 'Denbighshire Coalfield'
Nine Foot Rider	Nine Foot Rider	—
Nine Foot	Nine Foot	Nant Rider, Nant or Wall and Bench
Nant	Yard	Nant, Stone, Wall and Bench, Four Foot or Two Yard
Ruabon Yard	Cannel	Ruabon Yard, Lower Yard, Top Queen, Prince, or Wall and Bench
Premier	Wall and Bench or King	Wall and Bench, Queen or Wallsend
Llwyneinion Half Yard	Half Yard, Queen or Lower Queen	Llwyneinion Half Yard, Half Yard, Lower Yard, Lower Queen or King
Chwarelau	—	Chwarelau



Resource areas are terminated at the 10m drift thickness contour

This figure is a simplified portrayal of 1:25 000 scale map 6 which should be consulted for detailed information

Figure 14 Bedrock resources

and shallow trial pits, displaying the veins themselves provides a good guide to the undermined areas. However, in the case of the deeper, usually more scattered shafts, these were not necessarily sited directly on the vein trends, and hence the positioning of the veins is subject to inaccuracy. A further problem is that many of the veins depart significantly from vertical, increasing the area of potential undermining.

The map shows the known shafts, some 200 in number; there are likely to be others which are now obscured. Some shafts have been capped, others are closed at surface (due to collapse) but may be open at depth. Some estimate of the depth of some of the closed shafts may be gained from the amount of spoil material surrounding the shaft site. These areas of spoil form ring-like ramparts around the shafts, which are themselves usually preserved as depressions. The larger the volume of spoil relative to the diameter of the shaft-site, the greater is the likelihood of it having been a deep shaft, rather than an ephemeral trial pit. It is increasingly common practice to attempt land restoration in areas of previous lead mining by bulldozing flat the made ground. Consequently in some areas, the number and density of shafts will remain unknown. A computer database containing information about the condition of known shafts at surface has been prepared by Clwyd County Council.

Ores are principally restricted to veins, joints, pipes and some bedding planes (see Summary of Geology, Annex A – Mineralisation). They occur as discontinuous deposits whose distribution and concentration are unpredictable. As modern large-scale base metal extraction tends to rely on prospects of predictable, albeit often relatively low, concentrations, the ore deposits in the area would seem not to be a viable prospect under present or foreseeable economic conditions. Furthermore, the extensive shallow-level removal of ores during the past would necessitate that future mining would have to exploit resources at some depth and this would pose problems of mine drainage.

Bedrock resources – except Coal/Metalliferous (Thematic Map 6, and Figure 14)

This map shows the distribution of areas within which bedrock resources, apart from coal and metalliferous deposits (Map 5), are or have been extracted and where potential may exist for further exploitation. Where applicable, the resource areas are shown as being limited by drift deposits more than 10 m thick since it is considered that most bedrock resources except coal and metalliferous deposits are unlikely to be exploited beneath an overburden which exceeds that thickness. It must be emphasized that this 10 m limit is only approximate as there are some parts of the study area in which there is insufficient borehole information or field evidence to permit the drawing of an accurate 10 m drift isopachyte.

Active quarries and pits and the larger disused quarries and pits are shown; sites of completely backfilled quarries and pits (where known) are also shown since these could represent a possible hazard for developers. Each quarry or pit, whether active or disused, is annotated to indicate the type of resource which was obtained from it; the same annotation is given with each heading in this description. A few of the disused quarries and pits lie outside indicated resource areas. These either

Table 2 Summary of mechanical and chemical property data from limestones (Adapted from Harrison and others, 1983)

Formation	Rock type (generalized)	Purity		Mechanical properties			
		Purity	Insoluble residue	Flakiness Index	AIV	ACV	AAV
Cefn Mawr	Dark argillaceous limestone with shales	Generally low purity	1.2 – 31.9	27 – 51	20 – 24	23 – 25	5.0 – 9.1
Loggerheads	Massive pale grey limestone	Very high purity	0.2 – 1.5	14 – 31	20 – 25	25	10.2 – 11.8

lie within resource areas which are too small to show on the map, or were for clay, a resource which is not shown in detail on the map (see under Clay).

Limestone (L)

There are two main outcrops of the Carboniferous Limestone, which has a total outcrop area of some 5 km^2. The first occupies the structurally complex southern side of Hope Mountain and extends westwards along the northern side of the Bala fault system through Ffrith to Black Wood. The second main outcrop lies to the south-west of the Minera Fault, on the north-west slopes of Esclusham Mountain. This area is the northern extremity of the limestone outcrop which extends southwards along Eglwyseg Mountain to the Vale of Llangollen. Additionally, there are small areas of Carboniferous Limestone within the Bala fault system between the southern end of Black Wood [SJ 265 540] and the western edge of the study area. Most of the outcrop is free from significant drift deposits.

Three divisions (formations) have been recognised within the Carboniferous Limestone, and their areas of outcrop are known in detail. The sequence of formations, their thickness variation, and a detailed description of the rock types in each formation are given in the Summary of Geology, (Annex A). Physical properties of the limestones and estimates of their purity, derived from Harrison and others (1983) and related to the new stratigraphy, are given in Table 2.

The limestones of the Cefn Mawr Limestone and Minera Formation have been grouped together on the resource map since they have similar characteristics. The significant difference between the formations is that the Minera Formation includes interbedded quartzitic sandstones which are not present in the Cefn Mawr Limestone. The limestones of the Cefn Mawr Limestone are interbedded with mudstones, with the proportion of mudstone increasing towards the top of the formation. The Minera Formation, which also includes interbedded mudstones, has been worked in the past for limestone and sandstone; the Cefn Mawr Limestone is at present worked by Tarmac Roadstone Ltd (North West) near Minera [SJ 251 519].

The Loggerheads Limestone, in contrast to the Cefn Mawr, is of very high purity and has a very low mudstone content. Together with the Cefn Mawr Limestone it is quarried near Minera.

Limestone is without doubt the single most important mineral resource within Clwyd. In the study area, however, resources are limited since the main limestone outcrops lie to the west on Eglwyseg Mountain and also to the north-west between Llandegla and Prestatyn (see Campbell and Hains, 1988). Additionally, in the Minera district, the limestone is thinner than on the northern side of the Bala fault system or southwards towards Llangollen. The underlying Ordovician rocks have been reached in some areas of the quarries and further scope for deepening them, especially in their western parts, is limited. In the Hope Mountain area the limestones are thicker, but the extensive structural complexity of the area militates against large-scale extraction; also much of the outcrop lies within the Minera Formation with its high content of sandstones.

The amount of theoretically workable limestone in the area (i.e. above the water table) is approximately 10^9 tonnes. In practice only a very small fraction of this is likely to be worked and many factors effectively reduce the amount of the resource actually available. These include geological factors such as the presence of shale and sandstone units in the upper part of the sequence and past mining for metalliferous deposits, areas sterilised by housing, and environmental factors such as the effect on topography. Nevertheless, less than 4% of the total volume has so far been extracted and one important result of this study is that the new detailed geological maps will enable the appraisal and future exploitation of the resource to be carried out more effectively now that the areal extent and thickness of the various limestone types is more closely defined.

The Loggerheads Limestone is of predictable and constant nature; it is of high purity and good aggregate quality and can generally be expected to be of sufficient strength and durability to be used as a roadstone (base and sub-base) and concrete aggregate (Harrison and others, 1983). The Cefn Mawr Limestone and Minera Formation contain limestones of similar aggregate quality but they also contain a high proportion of mudstone/shale waste; however, the association of limestone and shale can be particularly useful for cement production. The Minera Formation, however, has the additional problem that sandstone bodies within it detract from its value as a primary resource for the cement industry.

Clay (C)

The most important clay resources are those within the Ruabon Marl Formation, though clay has been worked at horizons within the Bettisfield and Erbistock formations. Additionally, there have been very small local workings in Till (Boulder Clay). Only the Ruabon Marl Formation clays are shown as a resource on the map. The only working pit is at Hafod [SJ 309 455], near Johnstown, operated by Dennis Ruabon Ltd for tile-making.

The Ruabon Marl Formation is some 200 m thick in the Hafod area, but only the red and purple mudstones in the lower and middle parts of the formation are of economic value. Nearly all the outcrop is obscured by thick drift deposits and workable resources are limited to the area around Hafod and to the south of the study area. Similar red and purple mudstones in the Erbistock Formation have been worked for bricks and terracotta goods at the Wilderness Pit [SJ 335 535] near Gresford and near King's Mills, Wrexham. The Erbistock Formation has not been included as a resource as there is a great variety of lithological types within the formation and also because almost all the outcrop is covered by thick drift deposits.

Mudstones and thin fireclays (See description of Thematic Map 5) occur throughout the Bettisfield Formation and also in the Halkyn Formation. They have been exploited for brickmaking, pottery and other purposes as at Llwyneinion [SJ 288 475] and Cae-llo [SJ 288 543]. They are not now utilised and since such clays and mudstones occur so commonly it is not feasible to categorize them as a resource on the map.

Some of the old clay pits have been or are being used as disposal sites for industrial or household waste.

Sandstone (S)

Two types of sandstone are shown on Map 6. These have been denoted as a) quartzitic sandstone and b) feldspathic sandstone. The Kinnerton Sandstone is not included as a resource as its outcrop is everywhere covered by thick drift deposits.

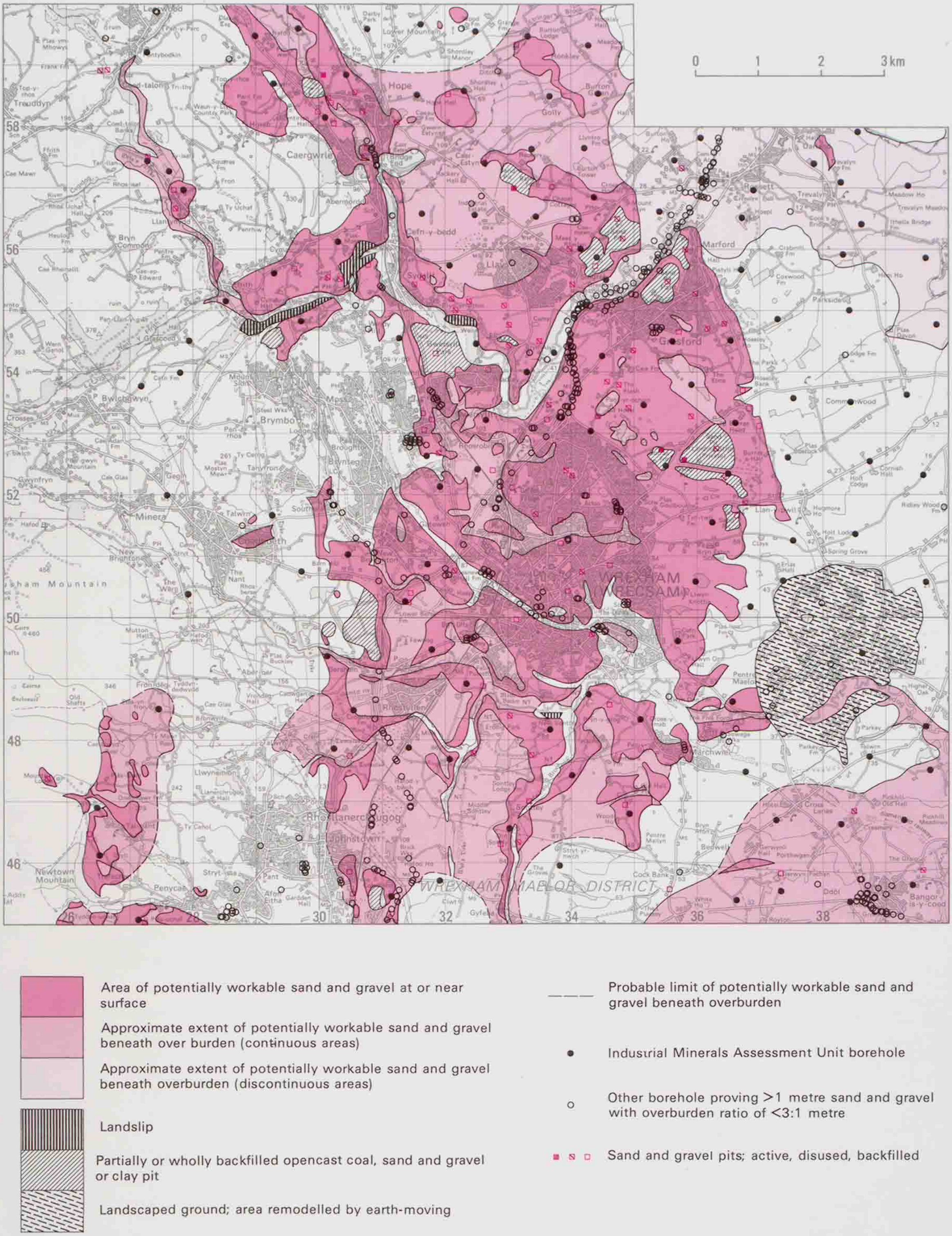
The quartzitic sandstones are those within the Minera Formation and the Halkyn Formation (except the Gwespyr Sandstone). They are sandstones with a very high quartz (silica) content and a low content of feldspar. In the lower part of the stratigraphical sequence these sandstones contain an appreciable proportion of calcium carbonate either as included fossil (shell) debris or as an intergranular cement. Normally the quartzitic sandstones are hard, but locally and unpredictably the more carbonate-rich types may weather to a disaggregated and very pure silica sand.

The feldspathic sandstones include the Gwespyr Sandstone at the top of the Halkyn Formation and all the sandstones within the Bettisfield Formation (Productive Coal Measures). They contain a higher content of feldspar than the quartzitic types and may also have an appreciable content of iron oxides. In general they are softer than the quartzitic sandstones and are more liable to weather along bedding planes or other planes of weakness in the rock.

Both types of sandstone have been widely exploited in the past. The basal sandstones of the Halkyn Formation have been worked for silica-brick making and roadstone in extensive quarries north and south of Bwlchgwyn and at New Brighton [SJ 275 505], near Minera. These sandstones have also been quarried at Waun-y-Llyn [SJ 285 579], and are being worked at present at Bryn y Gaer [SJ 315 576], near Hope. The Cefn Rock, within the Bettisfield Formation, was widely used as a building stone, with many quarries around Moss [SJ 305 535], Broughton and Gwersyllt. A sandstone within the Erbistock Formation, quarried at King's Mills [SJ 350 490] near Wrexham, was also used as a building stone; it is not included as a resource since its extent is not known. There are numerous small disused quarries in all these sandstones which provided local sources of stone for walling and building. The aggregate quality of the sandstones is not known in detail though their mineral composition and weathering characteristics suggest that the feldspathic sandstones are likely to be of poor to moderate quality while the quartzitic sandstones may locally be of good quality. However, there are a number of factors which militate against their exploitation for this purpose. Firstly, many of the sandstone beds, particularly within the Bettisfield Formation, are relatively thin and often change rapidly in thickness, and thus are not amenable to large-scale quarrying operations; secondly, the weathering characteristics of the sandstones are very variable and unpredictable, especially the quartzitic type where a hard sandstone can change laterally to a disaggregated sand within a few metres; thirdly, they are closely adjacent to very large resources of limestone of consistent and proven aggregate quality.

Sand and gravel resources (Thematic Map 7, and Figure 15)

This map shows the known distribution of sand and gravel within 1 metre of the surface. Deposits less than 1 metre in thickness have been omitted. The deposits are largely classified as Glacial Sand and Gravel on Map 2 – Drift geology. Areas of potentially workable sand and gravel (see below)



This figure is a simplified portrayal of 1:25 000 scale map 7 which should be consulted for detailed information

Figure 15 Sand and gravel resources

are also shown. These have been divided into those areas where the deposit is believed to be continuous or almost continuous beneath overburden, and those where it is thought to be discontinuous. Sites of active and former workings for sand and gravel are shown. At present there are three active pits within the study area, at Fagl Lane [SJ 300 586] operated by Welsh Aggregates Ltd, Borras Farm [SJ 355 529] operated by Alfred McAlpine Quarry Products Ltd, and at Bank Farm [SJ 332 573] operated by Astbury Quarries Ltd. The whole of the study area (except for a 2 km wide strip in the north-west, north of grid line 50 and west of grid line 27) has been previously assessed by the Industrial Minerals Assessment Unit (IMAU) of BGS and the results published (Dunkley, 1981; Ball, 1982). The boreholes drilled during that study are shown on the map, as are other boreholes which prove more than 1 metre of sand and gravel with an overburden ratio of less than 3:1. In their assessments a deposit stated to be 'potentially workable' must satisfy the following criteria:

1 The deposit should average at least 1 metre in thickness.

2 The ratio of overburden to sand and gravel should be no more than 3:1.

3 The proportion of fines (particles passing an 0.625 mm BS sieve) should not exceed 40 per cent.

4 The deposit should lie within 25 m of the surface.

For particle size analyses a grain size definition based on the geometric scale 1/16 mm, 1/4 mm, 1 mm, 4 mm, 16 mm, and 64 mm has been adopted. The boundaries between fines (that is the clay and silt fractions) and sand, and between sand and gravel are placed at 1/16 mm and 4 mm respectively. During the present study minor amendments have been made to the boundaries of the sand and gravel deposits on the published maps (Dunkley, 1981; Ball, 1982). Additionally, the areas indicated on these maps as being 'potentially workable' beneath superficial deposits have also been amended in the light of evidence from recent boreholes. No additional particle size analyses of deposits within the study area have been carried out.

A number of factors affect the ease of working of the sand and gravel deposits; these include their topographic form and the degree of lateral variation within them. At one site (Fagl Lane) the deposit is being worked from below the water table, by dredging. In some areas, as between Wrexham and Gresford, the deposits have a marked moundy topography with a number of enclosed hollows (kettle holes) which may be filled with peat and/or clay to a considerable depth. The variable thickness of the sand and gravel in such moundy areas, together with the infilled hollows, renders such deposits more difficult to work on a large scale than flat-topped spreads of sand and gravel as to the east of Wrexham from Borras Airfield southwards. All the sand and gravel deposits show rapid lateral changes of lithology. In particular the coarser gravels are often confined to irregular channels within a deposit of generally finer grade. The proportions of the various types of clast within the gravels also vary considerably. The main clasts are quartzites, limestones and Carboniferous sandstones, with smaller proportions of Lower Palaeozoic sandstones and siltstones and various igneous rocks. Coal forms a significant proportion of the clasts in some places. The proportion of Lower Palaeozoic clasts tends to increase towards the west and the igneous clasts towards the north, reflecting derivation from the Welsh and Irish Sea ice-sheets respectively. However, the sand and gravel deposits in general, and the Wrexham 'delta-terrace' (see Summary of Geology, Annex A) in particular, were largely deposited by water derived from both ice-sheets and the variation in clast content is minimal compared with that in the Welsh and Irish Sea derived tills.

Approximately 93 km^2 of the study area has sand and gravel either at the surface or concealed beneath overburden. The results obtained by the IMAU (Dunkley, 1981; Ball, 1982), with additional information obtained during the present study, indicate a total volume of deposit of about 9×10^9 m^3 (approximately 13.5×10^9 tonnes). Of this at least 20% has already been sterilized by the urban areas of Wrexham, Rhostyllen, Gresford, Llay and Hope. The areas of greatest potential resource lie along the Alyn valley from the northern margin of the study area southwards to Hope and thence eastwards to Llay and Burton; east of Wrexham between Gresford and the Clywedog valley; and south of Wrexham between Marchwiel, Hafod and Bersham.

ENGINEERING GEOLOGY

Solid rock (Thematic Map 8) and Drift (Superficial) deposits (Thematic Map 9)

The two engineering geology maps of the Wrexham area depict areas in which geotechnical conditions are broadly consistent. However, the maps are only summaries and cannot reflect detailed conditions on a site-specific basis. The maps, and the accompanying engineering geological report (Waine et al., 1990) present information that provides a better understanding of the general engineering geology of the area so that potential constraints on development can be identified and site-specific investigations better designed.

The boundaries between engineering geological units are based on the geological maps produced during the study. Map 8 shows the engineering geology of the solid rocks and Map 9 that of the drift (superficial) deposits. The groupings of materials with similar geotechnical properties were derived, in part, from data extracted from site investigation reports for locations within the study area.

A detailed discussion of the engineering geology and descriptions of the geotechnical tests for which results were analysed are given in the accompanying report by Waine et al., (1990).

Both maps should be examined to obtain an indication of ground conditions in a specific area. Map 4 will provide an approximate thickness of any drift (superficial) deposits. It should be noted that for areas shown as being drift-free, a mantle of weathered material and thin superficial deposits may be present. It is also possible that undetected pockets of thicker drift deposits may occur. Map 9 also shows undifferentiated made ground and fill.

It is emphasised that these maps present only a general guide to the ground conditions and that they should not be used, as a substitute for detailed site investigation, to ascertain the conditions prevailing at any specific site. However, the maps will be useful as an aid to better site investigation design, by indicating the conditions likely to be found at a given site. They are also a valuable source of general information relevant to planning issues.

Maps 8 and 9 are based, respectively, on the solid and drift geology (Maps 1 and 2). The relationship between the engineering geology units and the solid rock formations and the drift (superficial) deposits are shown in the map margins and Tables 3 and 4. These tables also show the engineering geological characteristics of each of the units. Simplified versions of the thematic maps are given in Figures 16 and 17.

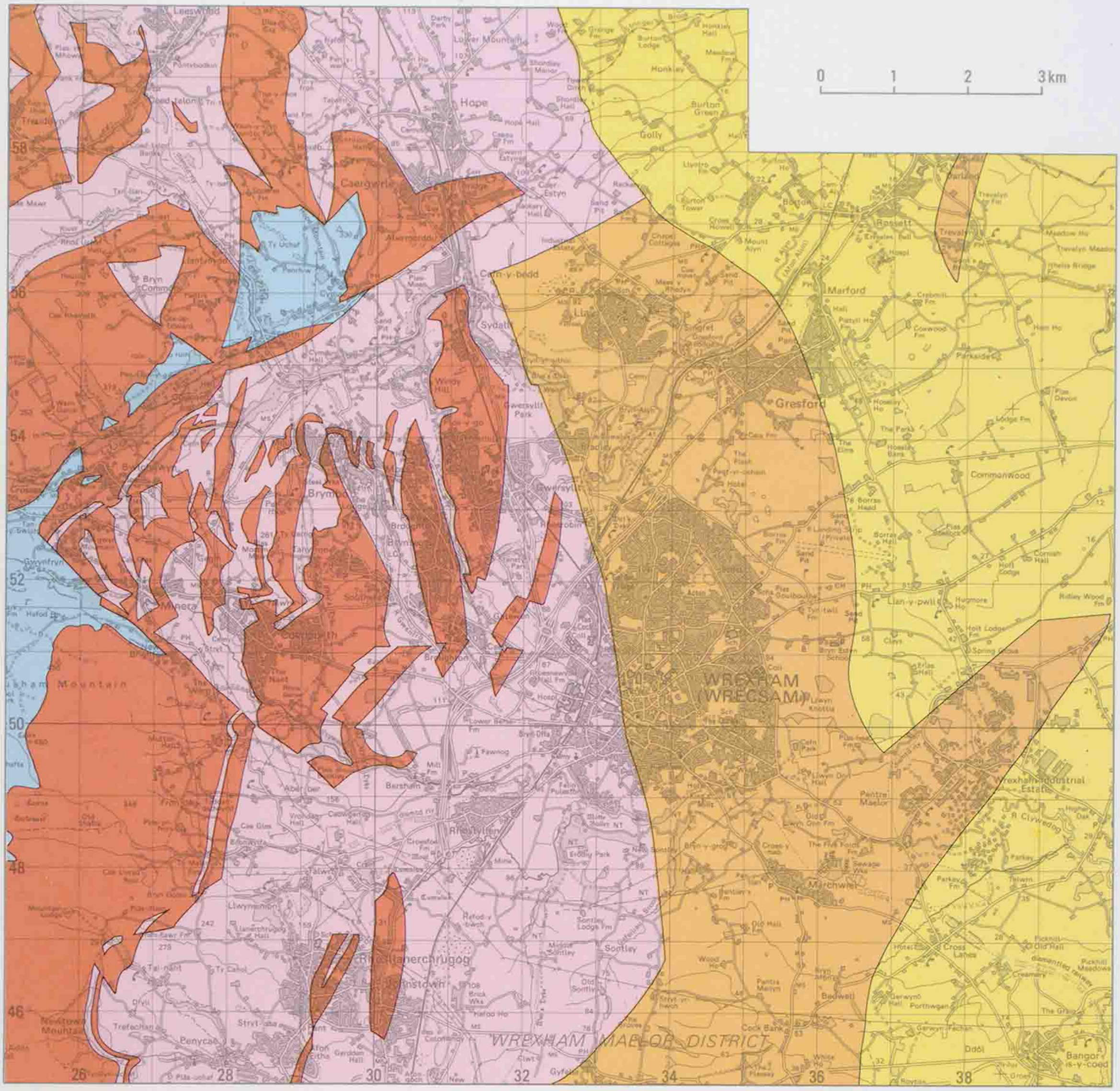
Summary values of geotechnical parameters for the units are presented in Tables 1 – 24 of the accompanying engineering geology report (Waine et al., 1990). Where information was available, these descriptions include comments on engineering design considerations in relation to foundations, excavatability, suitability as fill material and slope stability. These descriptions are summarised on the map margin.

Most of the units shown on the Engineering Geology of Solid Rocks map (Map 8) consist of 'engineering' rocks. However, because of weathering, some gradation between the states of rock and soil (in engineering terms) occurs, particularly in the case of the highly to completely weathered mudrocks of the Bettisfield and the Ruabon Marl formations which weather to a soft to stiff, silty clay.

SLOPE STEEPNESS

Slope steepness is an important parameter in planning and development, providing a constraint for some land uses. There is a close relationship between slope steepness and factors such as slope stability, the design of gradients of roads and railways, the use of agricultural machinery and certain types of construction plant, housing density and industrial development.

It is rarely possible to assign a precise slope steepness value to what can or cannot be done safely on a particular slope. Slopes in excess of 15° (1 in 4) may be stable in a coherent, massive limestone but unstable in a weak saturated clay. Most rocks and soils have a threshold value of slope steepness beyond which they become unstable. For any particular rock or soil type this value will depend not only on lithology but also on factors such as the presence or absence of discontinuities, the inclination of the bedding, the nature of the underlying and overlying strata, the degree of weathering, the hydrogeological conditions prevailing and vegetation cover. Therefore, the threshold slope steepness value for stability need not be the same for all slopes of the same lithology and will vary according to the inter-relationship of the controlling factors. However, given similar slope conditions, similar lithologies will tend to have consistent threshold slope values, but these may change with time as weathering of the slope progresses.



Limestones

Strong sandstones

Interbedded mudrocks and moderately strong sandstones

Weak sandstones

Mudrocks*

*Strong sandstones of the Ruabon Marl Formation are not mapped separately from mudrocks of this formation

NOTE: Three small outcrops (<100m across) of Ordovician turbidite siltstones and mudstones are not shown

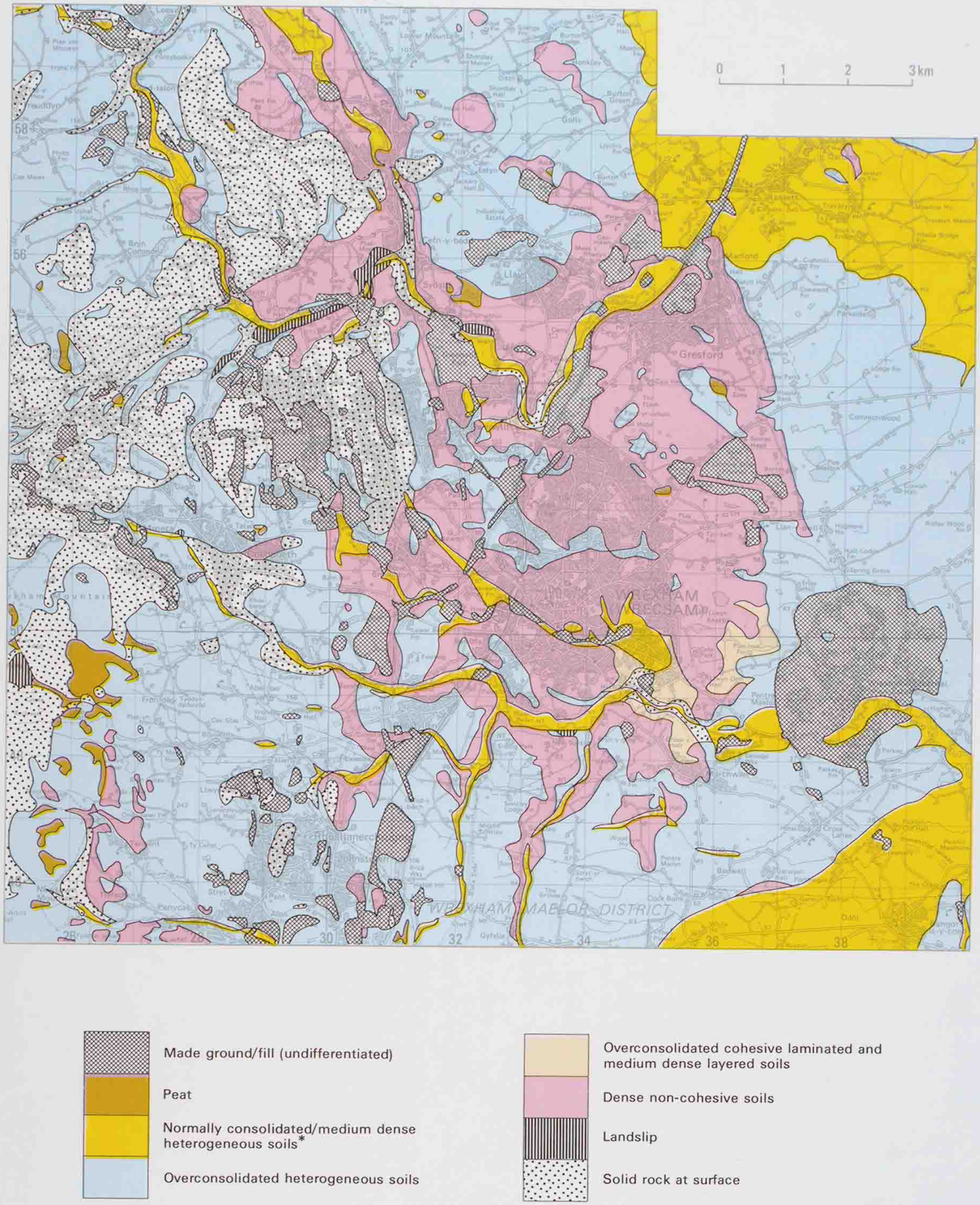
For full details, see Table 3

This figure is a simplified portrayal of 1:25 000 scale map 8 which should be consulted for detailed information

Figure 16 Engineering geology – solid

Table 3 Engineering geology units – solid geology

Engineering geology unit	Geological unit	Engineering geological characteristics
Limestones	Minera Formation Cefn Mawr Limestone Loggerheads Limestone	Variable mass strength dependent on frequency of argillaceous bands and discontinuities. Discontinuities enlarged due to solution; rockhead uneven. Natural and artificial (mining) cavities may be present. Rippable where weathered but blasting necessary in fresh rock. Suitable as fill after crushing. Design slopes should be no steeper than 1:1 where argillaceous bands present.
Strong sandstones	Ruabon Marl Formation sandstones Bettisfield Formation sandstones Halkyn Formation sandstones	Strong when fresh, moderately strong when moderately weathered. Weather ultimately to a dense sand up to 1.5 m thick. Excavation by blasting necessary for fresh rock but become rippable with increasing weathering.
Interbedded mudrocks and moderately strong sandstones	Erbistock Formation Coed-yr-Allt Formation	Mudrocks are well jointed and weather to a soft to hard silty clay to a depth of 1 – 3 m below rockhead. Sandstones are up to 1.5 m thick, thinly bedded and fissile. Excavation by ripping, or digging in weathered mudstones.
Weak sandstones	Chester Pebble Beds Formation Kinnerton Sandstone Formation	Coarse grained and cemented when fresh but weather to a sand which may be water-bearing giving rise to running conditions.
Mudrocks	Ruabon Marl Formation mudstones and shales Bettisfield Formation mudstones, shales and slitstones Halkyn Formation shales	Weather completely to a firm to stiff silty clay, recorded up to 4 m thick. Diggable and may be used as structural fill. However, weathered material softens rapidly on exposure and wetting. Should be placed soon after excavation and subjected to minimum construction traffic.



*Head deposits not mapped

For full details, see Table 2

This figure is a simplified portrayal of 1:25 000 scale map 9 which should be consulted for detailed information

Figure 17 Engineering geology – drift

Table 4 Engineering geology units – drift (superficial) deposits

Engineering geology unit	Geological deposit	Engineering geological characteristics
Made Ground/Fill	Made Ground/Fill	Including tips, infilled excavations, landscaped ground. Material very variable (eg household rubbish, industrial waste, mining waste). Engineering geology characteristics are site specific dependent on type of fill and method of emplacement. Detailed site specific investigation required.
Peat	Peat	Very soft; ranges from fibrous or decayed, to an amorphous organic silty clay. Up to 1.2 m thick in alluvial deposits; also found in upland areas. Highly compressible, consolidates rapidly with large settlements. Removal and replacement may be required. Acidic.
Normally consolidated/medium dense heterogeneous soils	Alluvial deposits River Terrace Deposits Head deposits	Alluvial deposits consist of soft silty clays c. 1.5 m thick; medium dense clayey fine sand, c. 3 m thick; medium dense silty sand and gravel from 0.5 to 7 m thick. River Terrace deposits as latter alluvial deposit but with cobbles and boulders and thin bands of firm silty clay and clayey silt up to 1.5 m thick. Clays compressible with low bearing capacity, unsuitable as fill. Excavations need support and dewatering. Head variable, typically sandy silty clays with gravel. Forms thin veneer on hillslopes, thickening to valley floors. May contain relict shear planes and be susceptible to mass movement failures. Coarser material may contain perched groundwater tables. Careful investigation by pitting necessary.
Overconsolidated heterogeneous soils	Till (Boulder Clay)	Mainly silty sandy clays with gravel cobbles and occasional boulders. Bands of sand and gravel which can be water bearing. Clays of low to intermediate compressibility with small settlements. Excavations stable in short term but may deteriorate on wetting. Suitable as fill at low moisture content.
Overconsolidated cohesive laminated and medium dense layered soils	Laminated Clay Till Glacial Silt	Laminated silty clay with bands of silt and fine sand (laminated clayey till) or well bedded clayey silts (Glacial silt). Laminated clay may be desiccated to c. 5 m from ground surface. Strength anisotropic. Excavations in laminated clay stable in short term but deteriorate with wetting. Glacial silt may run in excavation and is unsuitable as structural fill.
Dense non-cohesive soils	Glacial Sands and Gravels	Medium dense to dense sand and gravel with cobbles recorded up to 38 m thick. Medium dense sands and silty and clay sand bands present. Bearing capacity variable.
Landslip	Landslip	Variable composition; found on several lithologies on steep valley sides (>15°) and where toe undercut by streams. Careful investigation required to determine slope stability.

Slope steepness has a variable rather than absolute value, which will alter with changes in the factors controlling slope equilibrium. These changes can be brought about by natural processes or by the modification of the slope by engineering works. The controlling factors and the effect of changes on them are site-specific. Design judgements or slope stability assessment should be based on site measurements. No map of slope steepness is included with the report, but such data is held in digital form at the BGS Headquarters at Keyworth, Nottingham. This data was derived from the spacing of 5 m vertical interval contours on the 1:25 000 scale Ordnance Survey topographic maps. The values of slope steepness chosen as class boundaries are generally considered as bounding values for development, construction, agricultural and other land uses. The slope classification adopted in this study and its significance for land use are presented in Table 5.

HYDROGEOLOGY (FIGURE 18)

There is a limited amount of hydrogeological data for the study area and consequently it has been displayed on Figure 18 rather than as a 1:25 000 scale Thematic Map. This figure shows the main aquifers of the area, which are the Carboniferous Limestone, sandstones in the Millstone Grit (Halkyn Formation), sandstones in the Productive Coal Measures (Bettisfield Formation) and the Permo-Triassic sandstones (Kinnerton Sandstone and Chester Pebble Beds formations). It also shows the location of licensed wells, springs and adits, licensed landfill sites (Table 7) and contours on the potentiometric surface of the Permo-Triassic sandstones. The drift deposits have been omitted from this map for clarity; they are shown on Map 2. Chemical analyses of the water from selected sources are shown in Table 8. Problems related to aggressive ground water and pollution of aquifers are considered in the section on Physical and Chemical Constraints to Development.

The study area lies mainly within Hydrometric Area 67 (the Dee catchment), with the southern margin within Hydrometric Area 54 (the Severn catchment). The management of water resources lies in the hands of the National Rivers Authority (Welsh and Severn-Trent regions).

The main drainage of the area is by the River Dee and its tributaries, notably the Ceiriog. The southernmost parts are drained by the River Perry, a tributary of the Severn. The streams are moderately flashy with a base flow index varying from 0.49 on the Dee to 0.67 on the Perry. Extensive areas of the alluvial plain of the River Dee are liable to flooding or could be flooded if protective levees were breached or overtopped. These areas make up the 'Dee flood plain safeguarding area' (Figure 4) in which development is likely to be strongly influenced by the possibility of flooding.

The mean rainfall over the district is of the order of 700 mm/year over the lower ground to 900 mm/year over the higher ground. The mean evapotranspiration is considered to be about 450 mm/year. Infiltration is controlled largely by the thickness and permeability of the drift cover, varying on average between 50 and 250 mm/year.

Table 5 Slope steepness classes and examples of land use limitations (based on Small and Clarke, 1982)

Angle	Gradient	% Percent	Housing and construction	Construction machinery	Roads and rail lines	Agriculture
>15°	About 1 in 4	>27	Developing sites for housing and construction likely to require expensive precautionary works with attendant risk of triggering land instability in some locations.	Road building difficult. Absolute limits are approached for most wheeled vehicles	Road and rail construction require increased site works (e.g. cuttings) and costs as gradients increase. In general, it is more economic to locate roads and rail lines to take advantage of less steep terrain.	Slopes to steep for tractors. Mainly given over to pasture.
11–15°	1 in 5 to about 1 in 4	20–27				Absolute limits are approached for tractors. Ploughing generally not possible without contour terraces.
7–11°	1 in 8 to 1 in 5	13–20		Problems for wheeled vehicles.		Problems for wheeled tractors and combine harvesters.
3–7°	About 1 in 20 to 1 in 8	6–13	Development for housing and construction likely to require increased costs for site preparation.	Use of wheeled vehicles becoming difficult.		Problems for large-scale mechanical agriculture.
<3°	Less than about 1 in 20	<6	Suitable for most land uses where other physical constraints are not present and where no risk of flooding. Poor drainage on flat clayey ground and flood risk present on flat, low lying areas.			

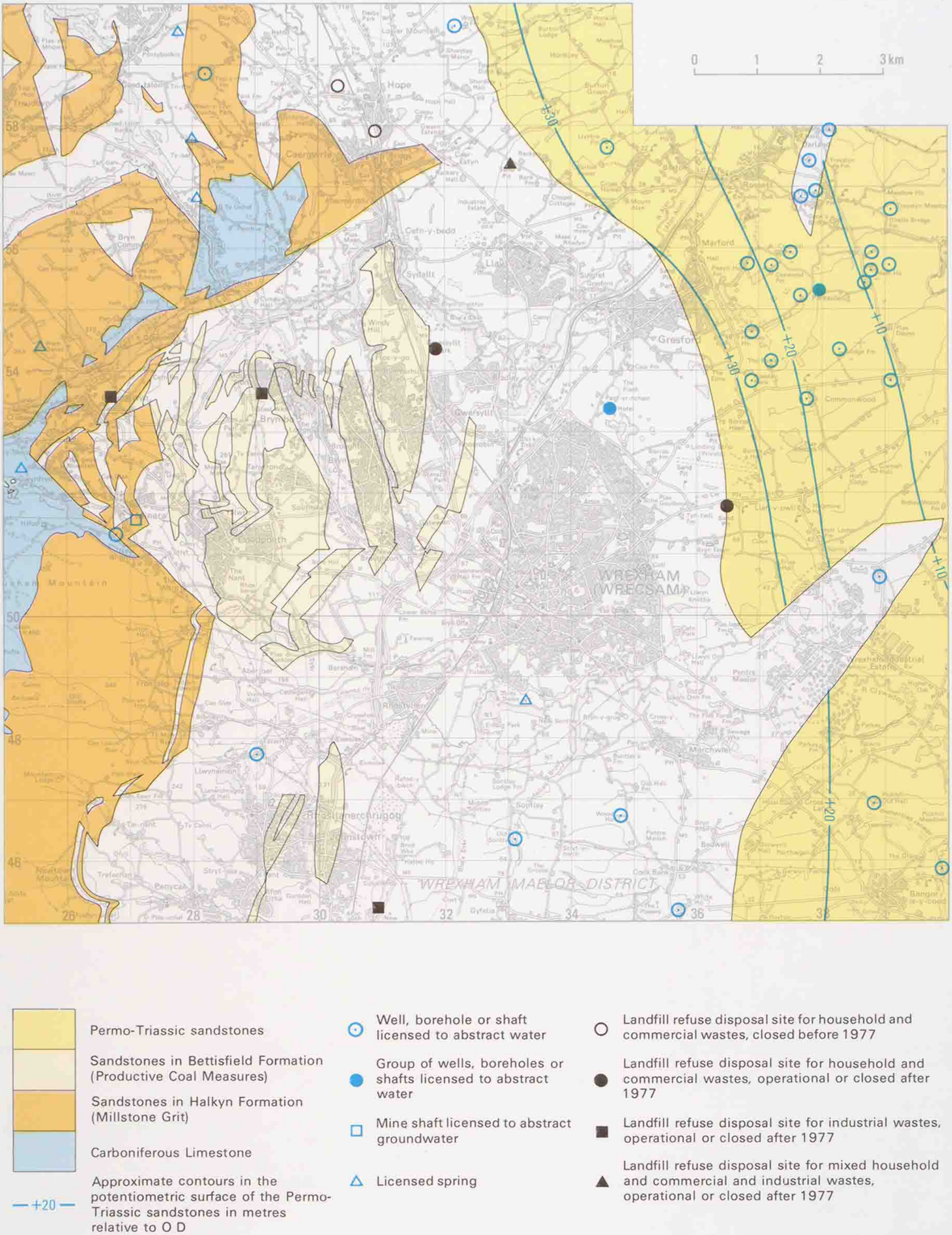


Figure 18 Hydrogeology

Table 6 Licensed abstraction from shafts, boreholes and springs in the study area (m^3/day)

	Carboniferous Limestone	Halkyn Formation	Bettisfield Formation	Permo-Triassic sandstones	Drift
Public supply and industrial	—	—	32617	1091	—
Agricultural and domestic	54	19	37	311	125
TOTALS	54	19	32654	1402	125

Total licensed abstraction for district is 34 254 m^3/day

A consideration of the hydrogeology of the formations present within the district follows.
Carboniferous Limestone

The limestone outcrop occupies only limited areas within the study area. While it has some potential for groundwater supply from boreholes, drilling for water is highly speculative as the limestones have minimal primary porosities and permeabilities, and groundwater movement is restricted to fissures enlarged by solution. There are no records of shafts or boreholes constructed specifically for water supply in this district. However, two spring sources are licensed for a total take of 54 cubic metres per day (m^3/d) for agricultural and domestic purposes.

Halkyn Formation (Millstone Grit)

This formation comprises a multi-layered aquifer with groundwater obtainable from shafts and boreholes intersecting sandstone and grit beds; the intervening mudstones and shales are rarely permeable. Although the arenaceous beds offer some intergranular storage, groundwater flow is generally through joints and fissures. Shallow shafts and boreholes may yield small supplies of the order of a few cubic metres per day, sufficient for domestic and small agricultural demands. Licensed sources comprise three springs and one shallow shaft with a total licensed take of 19 m^3/d. Groundwater quality is likely to be reasonably good with a total hardness of less than 300 milligrammes per litre (mg/l) as $CaCO_3$. The main problem is generally with iron which is locally present in concentrations of more than 1.0 mg/l; such values may impart a taste to the water and also cause staining of laundry and bathroom fittings.

Bettisfield Formation (Productive Coal Measures)

This formation also comprises a multi-layered aquifer with groundwater being found in the sandy beds. For the few records that are available for this district, it would appear that a borehole of 300 mm diameter penetrating 30 metres of saturated rock would on average yield between 60 and 70 m^3/d for a drawdown of 10 metres. There would be approximately a 20% chance that the yield would be less than 20 m^3/d for the same drawdown. However, abandoned coal workings do provide a large although localised storage; a borehole (25 SE/43) at the Brymbo steel works [2921 5354]

Table 7 Landfill waste disposal sites in the study area

Site	National Grid reference	Type	Status
Willow Hope	SJ 309 579	1	Closed before 1977
Fagl Lane	SJ 303 586	1	Closed before 1977
Tatham Road	SJ 309 451	2	In use or closed after 1977
Astbury's Quarry	SJ 330 574	3	In use or closed after 1977
Gwersyllt	SJ 318 543	1	In use or closed after 1977
Bwlchgwyn	SJ 267 535	2	In use or closed after 1977
Brymbo	SJ 291 531	2	In use or closed after 1977
Llanypwll	SJ 365 518	1	In use or closed after 1977

Types: 1. household and commercial 2. industrial 3. mixed

penetrated such workings and yielded 1700 m^3/d for a drawdown of 27 metres. The old Park Day Level (25 SE/1446) [2712 5160] and Speedwell Shaft (25 SE/1428) [2682 5132] are each licensed for a take of 9800 m^3/d. The total licensed abstraction from the Bettisfield Formation is 32 654 m^3/d. Of this, only 37 m^3/d is taken from shallow shafts and springs for agricultural and domestic use, while the rest is used for public supply and for industrial purposes, mainly from old coal workings. In a way, it is remarkable that a formation that is generally considered to be but a poor aquifer can supply such large yields of groundwater, albeit from large and extensive systems of shafts and levels.

Under natural conditions, groundwater in the Bettisfield Formation may be of fair quality, with a total hardness of less than 300 mg/l, and a chloride ion concentration of less than 30 mg/l (as Cl). Iron, in shallow shafts and boreholes, may be present in low concentrations, but does tend to increase with depth. Water drawn from old coal workings may be significantly more mineralised. At the Brymbo site, the total hardness was over 440 mg/l, about half of which was non-carbonate hardness, while the chloride ion concentration was more than 40 mg/l. The concentration of iron exceeded 4.0 mg/l. Elsewhere, under similar conditions, iron concentrations of more than 10.0 mg/l and manganese concentrations of more than 7 mg/l have been recorded.

Permo-Triassic sandstones

This is the only aquifer, in the generally recognised sense, within the study area. The sandstones are generally weakly cemented with a porosity ranging from 20% to 30%. Intrinsic permeabilities vary, but even the higher values are significantly less than the hydraulic conductivities encountered in the field. This is because groundwater movement is controlled by fissures that provide by far the greater part of the permeability and are present even to depths of 100 metres. Transmissivities and borehole yields may vary considerably depending upon the degree of development of the fissures, but it is unusual for a "dry" borehole to be drilled. Water in the fissures is supplemented by inflow from pores within the rock matrix. A study of borehole performance in the general region, including Cheshire, suggests that the average yield of a borehole of 300 mm diameter penetrating 30 metres of saturated rock would be of the order of 700 m^3/d for a drawdown of 10 metres. There would be

Table 8 Chemical analysis of water sources

Accession Number (SJ)	National Grid Reference	Location	TDS	TH	CH	Ca	Mg	Na	K	HCO_3
25 NE/564	2910 5900	Pen-y-wern		250	214					
25 SE/2B	2923 5214	Vron Colliery								
25 SE/43	2921 5354	Brymbo Steelworks	1032	447	227	91	53.5			495
34 NW/1	3146 4817	Bersham Colliery								
34 NW/384	3308 4628	Old Sontley	334	320	168	67.4	37	11.8	3.2	110
35 NW/26	3449 5739	Fields Farm, Burton						12.8		297
35 NW/324	3126 5543	Cefn-y-bedd								
35 NW/386	3236 5859	Shordley Hall, Burton	164	101	71	36.5	2.4	12	6.28	71
35 NE/14	3536 5867	Golden Grove, Burton	322	260	260				2.4	
35 SW/28	3356 5005	Border Brewery, Wrexham	474	333	203					
35 SE/2	3793 5483	Parkside, Allington								
35 SE/81	3624 5177	Llan-y-pwll	634	395	208	139	11.4	29.2	2.77	208

Accession Number (SJ)	Cl	SO_4	NO_3	Fe	Mn	pH	Balance	Date	Aquifer	Type
25 NE/564	21	37				7.5		Dec 72	Drift	Spring
25 SE/2B	35			91	7.5	6.4		May 77	Coal Measures	Well/Adit
25 SE/43	42.4		0.09	4.4	0.14			Aug 80	Coal Measures	Well/Adit
34 NW/1	185					8.3		Dec 76	Coal Measures	Well/Adit
34 NW/384	31.5	44.9	5.09	0.06		7.1	– 47%	Jul 80	Drift	Well/Adit
35 NW/26		56		0.28		7.3		Dec 78	Drift	Well/Adit
35 NW/324	26			46	3.1	6.3		Sep 77	Coal Measures	Well/Adit
35 NW/386	17.1	296	2.16	0.09	0.086	7.16	–15%	Jan 84	Drift	Well/Adit
35 NE/14	16			0.27	0.24	7.4		Dec 66	Permo-Trias	Well/Adit
35 SW/28	60	117				7.46		Apr 48	Coal Measures	Well/Adit
35 SE/2	27					7.6		May 73	Drift	Well/Adit
35 SE/81	57.4	74.7		<0.02	<0.01	7.51	– 29%	Apr 84	Drift	Well/Adit

TDS = Total Dissolved Solids. TH = Total Hardness, CH = Carbonate Hardness (both as $CaCO_3$). Units in mg/l (except for pH).

approximately a 20% chance that the yield would be less than 230 m^3/d for the same drawdown. However, a borehole (35 SE/53a) of 300 mm diameter at Messrs Kelloggs in Wrexham [3893 5068] yielded more than 1000 m^3/d for about 34 metres of drawdown even though it was lined out to within 10 metres of the bottom. It is, however, uncertain if this borehole is in the Permo-Triassic sandstones or the Erbistock Formation. The total licensed abstraction from the Permo-Triassic sandstones is 1402 m^3/d. Of this, 311 m^3/d are taken from 22 boreholes and shallow shafts for agricultural and domestic use, while the remainder is for a single industrial source. There are no public supply sources located within this aquifer in the Wrexham district.

The quality of groundwater from the Permo-Triassic sandstones is generally very good, with a total hardness of 250 to 350 mg/l. The chloride ion concentration is usually less than 30 mg/l. While analytical data are rather sparse within the district, the concentrations of iron and manganese may approach 0.3 mg/l.

Drift deposits

Groundwater has also been exploited from the more permeable of the drift deposits, notably the sands and gravels. These are most widespread around Wrexham and Gresford; they also extend eastwards for some distance under impermeable cover and give rise to artesian conditions on the Wrexham Industrial Estate and elsewhere. In the coarser gravels, shallow wells can sometimes provide good yields. A borehole (35 SW/15) of 150 mm diameter and 10.6 metres depth at Wrexham [326 507] yielded nearly 550 m^3/d for a drawdown of 1.2 metres; in this particular case, much of the yield may have in fact come from induced recharge from the adjacent river. In general, yields are very variable, the mean being of the order of 20 m^3/d, and 20% being less than 5 m^3/d. Eighteen sources, mainly shallow shafts and boreholes, but with a few springs, have been licensed for a total take of 125 m^3/d; all are for domestic and agricultural use. Under natural conditions, the groundwater is characterised by a low total hardness (less than 200 mg/l) and often by high concentrations of iron and manganese. In agricultural districts, high concentrations of nitrate are commonly found.

GEOLOGICAL FACTORS FOR CONSIDERATION IN LAND-USE PLANNING

Introduction

Interpretation of geological information may be required if planning policies are to be applied in the most cost-effective manner. The main areas in which geological conditions affect land-use planning are:

Mineral resource potential (Thematic Maps 5, 6, 7, 10 and Figure 19)

Physical and chemical constraints to development (Thematic Maps 8, 9, 10 and Figure 20)

Mineral resource potential

The thematic maps provide a data source with regard to mineral resources and their working. They delimit the various finite bedrock and drift resources (Maps 6 and 7) and provide information on the quality of the deposits. Such information may assist in avoiding the sterilisation of valuable resources by development, including the effective siting of plant. A summary of the main mineral resources, except coal, is shown on Figure 19. Water resources are considered in the section on Hydrogeology and in Figure 18.

Sand and gravel

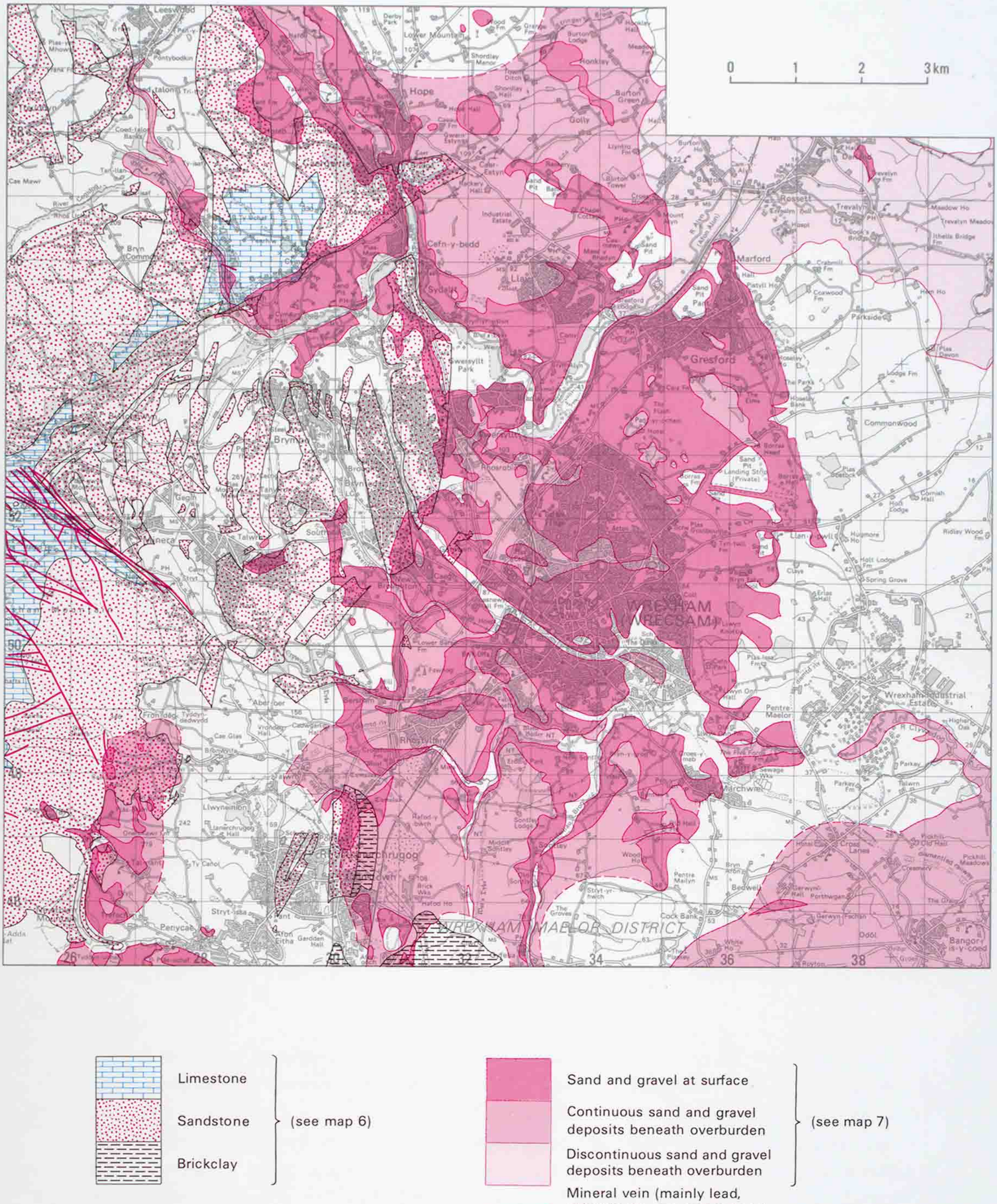
Significant sand and gravel deposits occur in many parts of the area, particularly around Wrexham and northwards to Marford and Hope (Map 7). Currently three sites are exploited for aggregate production, and deposits have been worked at other sites in the past.

Resources at surface and beneath limited overburden cover approximately 93 km^2. Deposits are relatively thin and rarely exceed 30 m in thickness; consequently despite the large extent of the resource area its maximum theoretical volume is limited (about 13.5×10^9 tonnes). Extraction in commercially viable quantities necessitates pits of large areal dimensions, which are relatively ephemeral compared to those associated with bedrock quarrying. The deposits tend to occur in areas of higher grades of agricultural land, or in close proximity to built-up areas, or in areas identified as being of high amenity value. Already some 20% of the theoretical resource has been sterilised by urban development. It should be noted that sand and gravel deposits often occur as moundy topographic features and their removal alters the landscape in a way which is hard to restore to its original form. These factors raise problems for the definition of future resources.

Potential resources, including concealed deposits, were identified by the Industrial Minerals Assessment Unit of the British Geological Survey (Dunkley, 1981; Ball, 1982). Areas of greatest interest appear to lie along the Alyn valley from the northern margin of the study area, southwards to Hope and thence eastwards to Llay and Burton, east of Wrexham between Gresford and the Clywedog valley, and south of Wrexham between Marchwiel, Hafod and Bersham. The deposits are very heterogeneous and vary greatly in thickness. Consequently the quality of the resource can only be proved by site-specific investigations.

Limestone

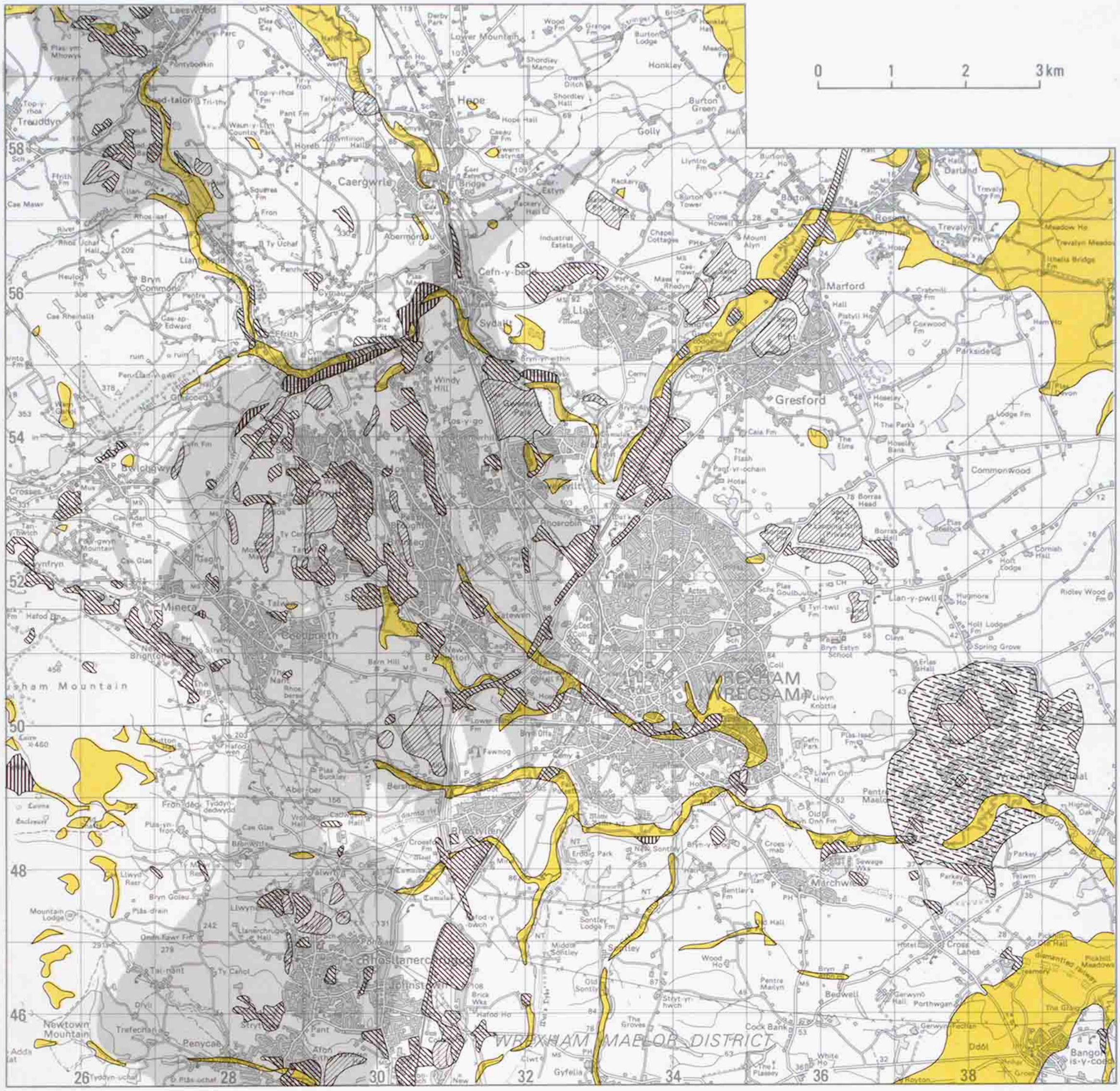
Only a small area (5 km^2) of limestone outcrop is present within the study area, with the theoretical amount of resource totalling some 10^9 tonnes. However, this forms part of the extensive Carboniferous Limestone outcrop in north and east Clwyd which provides a valuable resource for aggregate, cement, industrial and agricultural purposes. The outcrop within the study area has been divided into three formations with distinct resource characteristics (e.g. purity, limestone to shale ratio (Table 2)). Of these, the Loggerheads Limestone is of high purity with minimal shale content. The limestones of the Cefn Mawr Limestone and Minera Formation are also of high purity, but are interbedded with shales and, in the Minera Formation, sandstones also. Aggregate is produced from one site in the study area and has been extracted from a number of other sites in the past (Map



Limestone, sandstone and brickclay areas are limited by the 10m drift thickness contour

This figure is derived, and compiled, from information on 1:25 000 scale maps 5,6 and 7. Possible coal resources not shown (see text).

Figure 19 Mineral resource potential



Soft ground

Quarry, pit or opencast infill

Artificial deposits on natural land surface (Made Ground)

Landscaped ground

Mine workings possibly present within 30 metres of ground surface

Landslip

NOTE: Land outside the above areas is not known to be subject to significant physical constraints but still requires proper site investigation before development. Mineral resource constraints are shown on Figure 19.

This figure is a simplified portrayal of 1:25 000 scale map 10 which should be consulted for detailed information

Figure 20 Geological factors for consideration in land-use planning

6). Apart from its resource potential, limestone is also a significant source of groundwater outside the study area and, as such, requires protection from inappropriate development or contamination.

Coal

Underground mining of coal by shallow or deep methods (pillar and stall or longwall) and, more recently, opencast mining, has been a major industry in much of the central part of the area in past years (Map 5). The last deep mine closed in 1987; at present there is no deep mining and only one opencast site is working. Economic considerations suggest that future extraction is likely to be possible from limited opencast sites only. The general location of potential opencast coal resources is coincident with the area in which there may have been mining at shallow depth; on Map 10 this is defined as the outcrop of the Bettisfield Formation (Productive Coal Measures) where the drift cover is less than 30 m thick. Within that area workable resources are likely to be at or above the level of the lowest normally worked seam, the Llwyneinion Half-Yard. The potential for opencast extraction depends on a number of factors apart from environmental considerations. These include the number, thickness and quality of individual seams in any given area, the thickness of overburden and the extent to which the seams have already been removed by underground mining or disturbed by faulting.

Sandstone

Sandstone has been worked extensively in the past for building and walling stone and for refractory materials. At present, only one quarry is working, at Bryn y Gaer [SJ 315 576], near Hope. Sandstones of differing resource characters are identified in the report (see Map 6). These resources are scattered widely across the area and most appear to be of little economic importance. Thus, resource sterilisation of sandstone is unlikely to be a major planning consideration.

Brickclay

Brickclay (for tile making) is extracted from one site in the Ruabon Marl Formation. Although the outcrop of this formation covers an extensive area it is almost entirely covered by thick superficial deposits. Consequently, apart from the small area indicated on Map 6, sterilisation of this resource is unlikely to be a problem. Fireclays were worked in open pits or mines at a number of horizons within the Productive Coal Measures, usually in association with coal; however, the deposits are generally thin and not of great economic importance.

Lead, zinc and copper ores

Considerable mining of lead and zinc, and a little copper, took place largely in the second half of the nineteenth century but none is now extant. It was restricted to the area south and west of Minera. Although resources still exist, particularly at depth, their extraction is uneconomic in present or foreseeable terms due to drainage problems and the unpredictable nature and quality of the resource. This aspect is therefore not considered a significant concern for future planning. As with coal mining, it is the results of mining which provide the most important considerations for development and land use.

Physical and chemical constraints to development

The main physical constraints which may affect land-use planning decisions are shown on Map 10 and in a simplified version in Figure 20. In addition it gives a summary of other factors which may also affect planning decisions, and reference is made to the appropriate Thematic Map.

Slope stability

Natural slope instability poses few problems to planning and development in the study area, but modifications by engineering works which adversely alter the conditions controlling slope equilibrium may trigger mass movements locally, for example, in excavations and cuttings. Such failures are most likely to occur in the drift (superficial) deposits and in the weathered mudrocks. Steep slopes are not necessarily inherently unstable (see section on Slope steepness), but they may impose cost constraints on site development. The likely constraints are listed in Table 5.

Landslips (Map 10) have been observed on numerous rock types; they have in common a location on steep valley slopes (in excess of 15°), which are at present occupied by a river or stream. The largest landslips have occurred in mudrocks within the Bettisfield Formation, e.g. at [289 548], often originating from just beneath a sandstone/mudrock junction. The largest slip which is not within mudrocks [252 494] occurs within limestone overlain by sandstone and may have been caused by failure along a bedding plane since the angle or inclination is sub-parallel to that of the slope. Smaller slips have been observed within drift deposits which are being actively eroded by watercourses.

It is advisable to suspect the presence of landslips, where the above-mentioned factors are found in combination, even though landslipping at a selected site may not be indicated on published maps. Site investigations should determine the presence or absence of landslipping, and obtain the necessary soil strength and other parameters to enable a stability analysis to be carried out for the proposed slope profile after completion of construction work. Trial pitting and careful logging and sampling may be the most appropriate investigation method, depending upon the depth of slip planes.

Head deposits (variable deposits, mainly of silt and clay, formed under periglacial conditions; also recent hillwash) have not been mapped separately and are not indicated on the maps. Where they are greater than about 1 m in thickness they have been included with till. Such deposits need to be treated with caution as they may contain relict shear planes. Even sites on low angle slopes can be affected. Surface bulges may indicate recent ground movements which can be reactivated by construction works. It is also important to note that head deposits of less than 1 m thickness are widespread. Trial pit excavation and detailed logging during excavation is recommended. Shear planes are often exposed during excavation and can be identified by their polished, often slickensided surfaces. Logging the sides of an excavation pit alone will not necessarily reveal the shear planes.

Foundation conditions

Compressible Soils (soft ground) The compressibility of a soil (see Glossary for an engineering definition of 'soil') may be defined as the volumetric strain per unit pressure increase. The overall effect of imposing a foundation load on a normally consolidated deposit is to compress the deposit. The vertical component causes a vertical movement of the foundation due to elastic bending and reorientation of the soil particles. Excess hydrostatic pressure is gradually dissipated by expulsion of water from the soil voids, giving rise to time dependent volume change. The vertical component of the change is called the consolidation settlement.

Soils which experience relatively large amounts of settlement, or differential settlement are problematic, and can be identified by their geotechnical parameter values obtained from laboratory tests. These soils are predominantly very soft to soft, normally consolidated clays, which are often organic, and peats. In the study area, such deposits are found in the valleys of the water courses (alluvium) and within approximately circular, marshy depressions known as kettle holes (Maps 2 and 10); hill peat is present as a thin cover on parts of the eastern slope of Esclusham Mountain. Except on the hills the two lithologies are often interbedded, with peat forming lenses rather than discrete beds. In the kettle holes, which are prominent within the glacial sands and gravels between Wrexham and Gresford, soft deposits have been recorded as being between 10 and 20 m thick and are best avoided for building purposes if possible. In the river valleys and on the hills the thickness probably does not exceed 2.5 m, and removal and replacement with compacted hardcore has been recommended. Where it is thicker, this may be uneconomic, and ground treatment is required before shallow foundations can be utilised, for example by reinforcing the alluvium with stone columns by the vibroreplacement technique. Alternatively, end bearing piled foundations may be employed to transfer heavier loads to more competent strata beneath the soft deposits, where present. Caution should be exercised where the clay is soft to firm as it is often desiccated at the surface, becoming softer with depth.

Running Conditions This term refers to predominantly granular soils which are saturated with water and which may flow into excavations and boreholes due to the release of pressure. Under high hydrostatic pressure the material can rapidly enter the excavations as a fluidised flow. Trial pits become unstable and collapse, and borehole drilling is hampered. Running conditions have been reported when excavating within alluvial sands and gravels adjacent to water courses, glacial silts, sands and gravels within till and weathered Kinnerton Sandstone Formation sandstone close to the river Dee near Bangor-is-y-coed. Sheet pile cutoffs, shoring and well point dewatering have been employed to maintain stable excavations.

Aggressive Groundwater When the concentration of sulphates present in groundwater and in soil exceeds a threshold value, any buried concrete structures will be attacked, corroded and weakened unless special cement types are used. Similarly where acidic groundwater and soils are found, buried structures and services can be corroded. As the concentration of corrosive substances increases so does the necessity of utilising Sulphate Resisting Portland Cement for foundations.

The highest concentrations of SO_3 have been obtained from sites in the vicinity of colliery spoil heaps in the Gresford area.

Acidic groundwater is associated with peat and buried structures within peaty soils should be designed to withstand corrosion.

Cavities Certain strata in the area contain natural and artificial cavities which may be near, or at, surface. Firstly, natural solution cavities are present in the limestones and may be infilled by drift deposits washed into them. Secondly, there are disused mineral workings within veins in the limestone and Halkyn Formation sandstones around Minera; also, the Bettisfield Formation strata have been mined for coal, ironstone and fireclay, and disused shafts, adits and old workings may lie close to the surface. Map 10 shows the areas in which shallow old workings for coal are most likely to exist. They cover the outcrop of the Bettisfield Formation, but exclude those areas with a drift thickness exceeding 30 m. These hidden cavities and soft zones will reduce the bearing capacity of overlying strata and must be identified during the investigation. The position of old workings is often shown on Ordnance Survey maps. Known shafts and adits are shown on Map 5. If they are shown to underlie the site, specialist advice should be sought. Even so, not all workings can be detected in this manner, and Bell (1988) provides useful information with respect to means of locating abandoned shafts. Piggott and Eynon (1978) and Garrard and Taylor (1988) give valuable information on ground movements resulting from shallow mine workings. Old workings can also act as reservoirs for methane given off from coal seams (see below in section on Backfill etc).

Swelling Ground None of the geotechnical reports studied whilst compiling this report referred to, or tested for, swelling potential. Swelling takes place in some mudstone strata as a response to an increase in moisture content, and can give rise to relatively large volume changes which may damage foundations not designed to allow for swelling. Conversely desiccation allows the clays to shrink leading to excessive settlement. In view of this, swelling potential of weathered Bettisfield Formation mudstones was investigated and is documented by Entwisle (1989). For the rocks tested, swelling potential was found to be low. However, the results were obtained from a small number of samples from one locality. It is suggested that where plasticity levels are high (Liquid Limit 60, Plastic Limit 35) as found in rocks of weathering grades III and VI in the Deeside area, swelling characteristics are measured.

Backfill, Made ground and Landscaped ground

These three categories (shown on Map 10) all result from human disturbance or alteration of the natural ground surface. They have in common a variable composition, rate of consolidation and thickness; consequently their engineering properties are also variable (see Map 9 and the report on Engineering Geology (Waine et al., 1990). Additionally there is the possibility of hazardous or methane-generating components being present in backfill or made ground, and spontaneous combustion may occur in colliery waste under certain conditions (see below).

Methane This explosive gas can be generated by breakdown of domestic refuse within landfill sites. In some modern landfills, the gas has been utilised as a source of energy and the landfill designed accordingly. However, there have been reported cases, outside the study area, of explosions following the migration of gas from badly designed dumps, often dating from a time when the hazard was not appreciated. The Local Water Authorities have information regarding the types of waste buried in landfill sites which began operation since 1974 when the governing legislation was introduced. Pits and quarries backfilled before then may contain material which can break down to release methane.

Methane gas can also be given off from coal seams. Even if proposed works do not intercept seams, old workings can serve as zones of gas accumulation. During an investigation near Gresford, methane was detected, and a coal mine shaft suspected, though no record of its existence could be found. Methane is soluble, and care must be taken when tunnelling within or adjacent to coal bearing strata, as the gas can exsolve from groundwater and accumulate, in addition to migrating through discontinuities in its gaseous state.

Spontaneous combustion Colliery waste tips are vulnerable to spontaneous combustion during excavation, handling and placing. The main conditions necessary for it to take place are:

a sufficiently high combustible carbon content to provide a fuel (generally over 25%)

a sufficiently high iron pyrites content, oxidation of which generates the heat for spontaneous combustion

a sufficient availability of oxygen to sustain the combustion

For the tips near Gresford, the amount of combustible carbon was reported to be sufficient to cause fire. However, the iron pyrites content has been considered too low to generate spontaneous combustion, though this could not be totally ruled out.

When engineering works are carried out within colliery waste tips, compaction of embankments and shallow slopes are necessary to reduce the amount of available oxygen so preventing combustion. The slope faces should be protected with a thicker than average cover of clay or top soil.

Groundwater

Groundwater is obtained (Figure 18) from the Carboniferous Limestone, sandstones within the Halkyn and Bettisfield formations, the Permo-Triassic sandstones (Kinnerton Sandstone and Chester Pebble Beds formations) and from drift deposits (see section on Hydrogeology).

Superficial (drift) aquifers are very vulnerable to pollution from surface sources, due largely to the closeness of the water table to the ground surface and to the generally high permeability of the deposits.

Groundwater from bedrock aquifers is generally less vulnerable to pollution than that from superficial aquifers because of the filtering and attenuating effects of the unsaturated zone above the saturated aquifer. Consequently, it usually receives little treatment before being pumped into supply, and it is important that aquifers are protected from potential pollutants. The most vulnerable aquifers are those where water passes rapidly from the surface into the saturated zone. Such aquifers include the Carboniferous Limestone (Map 1) where most of the groundwater flow is through joints widened by solution, and sandstone in the Bettisfield Formation close to old workings (Maps 1 and 5).

There are two main types of potential pollutant sources, point and diffuse. Point sources include landfill and other waste disposal sites (such as sewage treatment works), and storage tanks for silage, fuels, industrial solvents and other chemicals. There are several sites that have accepted in the past or are currently accepting both household and industrial waste (Table 7). In general, these pose few potential problems for groundwater, either because they are located upon the outcrop of strata such as the Bettisfield Formation where any lateral spread of leachate is limited by the faulted and multi-layered aspects of the strata, or because the bedrock is covered by extensive deposits of relatively impermeable drift. Where the aquifer outcrop is drift-free, as is the case with the Carboniferous Limestone and some of the sandstones in the Halkyn and Bettisfield formations (Maps 1, 2 and 4), storage tanks can represent a serious risk to groundwater quality, particularly so where they are poorly constructed or in a bad state of repair.

Diffuse sources of pollution are largely represented by nitrates, applied to the ground as fertiliser, and biocides; both are widely used in agriculture. However, the risks in this district are generally low in respect of the two major water-yielding formations, the Bettisfield Formation and the Permo-Triassic sandstones, due to the extensive cover of relatively impermeable drift.

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ANNEX A SUMMARY OF GEOLOGY

The generalised geological sequence of the area is shown in Figure 6, and simplified solid and drift geology maps in Figures 7 and 8 respectively.

The following geological summary is a comparatively brief review of the main observational and interpretative findings of the desk study and the limited field survey undertaken in 1989. It also draws on evidence provided by the original geological survey of the area in 1881 and 1910-13, and subsequent partial revision in the 1970's. It is intended to be used as an aid to understanding the 1:10 000 geological base maps. In addition it lists, in context, much of the scientific literature relevant to the area.

The bedrock geology, in outcrop, comprises sedimentary rocks which range in age from high Ordovician (Ashgill) to Permo-Triassic, spanning some 200 million years. An overburden of unconsolidated glacial and post-glacial sediments (Quaternary to Recent) blankets much of the central and eastern parts of the area.

The bedrock sequence has, in general, a low easterly dip; however, in some areas, notably adjacent to the Bala-Bryneglwys fault system, the structure is considerably more complex due to faulting and local folding.

Ordovician

The oldest rocks of the area are of Ashgill (high Ordovician) age and are included in the Cyrn-y-brain Beds (Wedd, Smith and Wills, 1927). They occur only in three small areas, each less than 100 m across, in the bottom of limestone quarries at Minera and in the bed of the adjacent Aber Sychnant. They comprise grey cleaved turbidite siltstones and mudstones. They were deposited in a marine environment some 440 million years ago, probably as the distal product of turbidity currents.

Carboniferous

Rocks of Carboniferous age rest unconformably on the Ordovician sediments at Minera. Rocks of Devonian age are absent, as is the case in surrounding areas. The unconformity is an angular relationship, and the Carboniferous rocks, dipping gently to the east and south-east, overlie a previously folded and eroded Ordovician terrain.

Carboniferous Limestone (Dinantian)

The first major study of the Carboniferous Limestone of North Wales was carried out by Morton (1870) who recognised a general regional stratigraphy of Lower Brown, Middle White and Upper Grey limestones. Subsequent workers in this area have tended to substantiate Morton's classification (e.g. Neaverson, 1946). More recently, Somerville (1979a) has recognised three lithological units, approximately equivalent to those of Morton, in the Llangollen-Minera district.

The limestones (carbonate sediments) in this report have been described using the classification of Dunham (1962). This involves the interpretation of textural features and is ideally suited to rapid assessment based on field observations. The Dunham classification has four main categories: (1) grainstone, (2) packstone, (3) wackestone and (4) calcite mudstone. These are defined in the glossary with other less frequently used descriptive categories. In general terms the average grain size of the limestones decreases from grainstone through categories 2, 3 and 4. The individual carbonate grains are typically greater than 0.1 mm in size. Classification of the limestones in this way provides direct information relevant to the resource characteristics and engineering properties. Two types of carbonate grain are recognised, skeletal and pelloidal. The former were fragments of marine fossils and the latter were formed by sedimentary processes on the sea floor.

There are two main outcrops of the Carboniferous Limestone. The first occupies the structurally complex southern side of Hope Mountain and extends westwards along the northern side of the Bala fault system through Ffrith to Black Wood. In this area the lowest beds seen are within the Cefn Mawr Limestone. The second main outcrop lies to the south-east of the Minera Fault, on the north-west slopes of Esclusham Mountain, where a complete easterly-dipping sequence unconformably overlies Ordovician sediments. This area is the northern extremity of the limestone outcrop which extends southwards along Eglwyseg Mountain to the Vale of Llangollen. Additionally there are small areas of Carboniferous Limestone within the Bala fault system between the southern end of Black Wood [SJ 265 540] and the western edge of the study area.

The following sections give brief descriptive and interpretative details of the constituent formations:

Loggerheads Limestone Within the study area the Loggerheads Limestone is only present in a small area in and around the Minera limestone quarries [General grid reference SJ 273 521]. It is only about 60 m thick at Minera, although it thickens rapidly southwards (outside the study area) to 145 m on Eglwyseg Mountain. It is equivalent to the Eglwyseg Limestone Formation of Somerville (1979a). At Minera the basal 5 m is referable to the Leete Limestone (Ty-nant Limestone Formation of Somerville, 1979a); these beds have not been delineated separately on the map and for the purposes of this report are included in the Loggerheads Limestone.

The basal 5 m comprises pebbly bioclastic limestones and porcellaneous calcite mudstones; similar beds interbedded with pale grey poorly fossiliferous calcite mudstones occupy a further 10 m. The main body of the formation consists of pale grey, cream and white, massive to rubbly bedded, pseudobrecciated, pelloidal and skeletal packstones and subordinate packstone-grainstones.

An important feature of the limestone is the cyclic repetition ('minor cyclicity') of variations in lithology (Somerville, 1979a; Somerville and Strank, 1984a, 1984b). Within each cycle there is an upward increase in grain size with packstones passing up into grainstones. In lower parts of the formation the next cycle succeeds with or without an initial coarse-grained bioclastic deposit, and then a sharp reversion to finer-grained lithologies. In places, stylolites and small carbonate nodules are developed between cycles. Dark grey-brown mottling (patches of 0.5-2 cm) is also common in the lower parts of many of the cycles. Towards the top of the formation, the cycle boundaries are made more obvious by the appearance of irregular bedding plane surfaces within which are preserved fossil plant rootlets and roots. In some cases the surfaces possess hollows or pits within which light grey clays are preserved. The tops of these cycles are commonly rich in coarse fossil debris. Laminar carbonate (calcrete) is sometimes observed and iron oxide staining is common. The clays themselves have been interpreted as being potassic bentonites (altered volcanic ash) and represent a fossil soil (palaeosol) preserved on an irregular karstic (palaeokarstic) surface with depressions up to 50 cm deep. Each cycle is interpreted as a gradual shallowing of the general marine carbonate platform environment, with eventual emergence of a low topography land surface. The surface was subsequently drowned and followed by another phase of gradual shallowing of the sea. George (1974) and Ramsbottom (1973, 1977) suggest interpretations for the cyclicity. The occurrence of basal pebbly beds and the thinning of the formation at Minera has been attributed to contemporaneous uplift of the Cyrn-y-brain anticline (Somerville, 1979a).

Cefn Mawr Limestone This formation is the equivalent of the Trefor Limestone Formation of Somerville (1979a). On the northern side of the Bala fault system the basal part of the formation is faulted out; some 75 m of beds are seen. South of the fault system around Minera the formation, here present in its entirety, has thinned to about 60 m.

The formation mostly consists of thinly bedded, brown and dark brown, fine-grained pelloidal, skeletal packstones, wackestones and shaly mudstones. Interbedded, mainly towards the base, are thicker bedded, pale, coarser packstone-grainstones. Although the Cefn Mawr Limestone is substantially finer grained overall than the Loggerheads Limestone, a similar cyclicity is present. However the karstic surfaces and bentonites are rare, suggesting that emergence from the general low energy marine carbonate environment was less common.

The base of the formation is marked by an obvious colour change in the rocks, with the brown and dark brown limestones of the Cefn Mawr Limestone contrasting with the pale grey of the underlying Loggerheads Limestone.

A thick (3-4 m) mudstone (shale) bed is present in the middle part of the formation. This bed, the 'Main shale' of Earp (1958), has been mapped on the northern side of the Bala fault system. It is present to the south but has not been shown on the map. A coral-rich bed with abundant colonial and solitary corals occurs approximately 10 m above the 'Main shale'; it has also been mapped to the north of the fault system.

The upper parts of the formation are very mudstone-rich (c.50%). White and black chert nodules, up to 10 cm in size, often occur along selected bedding planes, mainly at high levels in the formation. The formation has a rich fossil content, and large brachiopods are very common.

Minera Formation This formation is about 180 m thick to the north of the Bala fault system, but only about 60 m thick to the south. It resembles the underlying Cefn Mawr Limestone except for the presence of massive and cross-laminated, fine- to medium-grained and occasionally pebbly, calcareous and quartzitic sandstones up to 25 m thick. The bases of the sandstones are sharp. Scattered fossils, trace fossils and carbonaceous material occur in the sandstones. Pebbles in the sandstones are generally of vein quartz. The sandstones, which represent a significant change in sediment provenance, are either marine transgressive sheet-sands or prograding fan-delta systems. They have not been mapped separately south of the Bala fault system.

Millstone Grit Series (Namurian)

Halkyn Formation – general The nomenclature and age of the beds between the Carboniferous Limestone and the Productive Coal Measures have been a matter of controversy for many years. To the north of the Bala fault system these beds were subdivided by Wedd and King (1924) into the Cefn-y-Fedw Sandstone (Millstone Grit Series) at the base, overlain by the Holywell Shales and Gwespyr Sandstone which they classified as 'Lower Coal Measures'. South of the fault the whole of the sequence was termed the Cefn-y-Fedw Sandstone by Morton (1876-9) and Wedd, Smith and Wills (1927); these beds include sandstones, conglomerates, cherts and mudstones. The sandstone at the top of the sequence was known as the Aqueduct Grit.

Correlation of the sequences across the Bala fault system was partly achieved by Wood (1937). He showed, by study of the goniatite faunas, that the Holywell Shales in the north were not of Coal Measures age but the equivalent of part of the Cefn-y-Fedw Sandstone to the south, and also that the Gwespyr Sandstone and Aqueduct Grit were approximate time equivalents since both were overlain by shales containing the Subcrenatum Marine Band, the basal marker bed of the Westphalian Series (Coal Measures).

In the present account, as in the Deeside Report (Campbell and Hains, 1988), the whole of the sequence between the topmost Carboniferous Limestone (Minera Formation) and the base of the Coal Measures (Bettisfield Formation) has been included within one formation, the Halkyn Formation, throughout the study area. In age it is approximately equivalent to the Namurian Series.

Halkyn Formation — north of Bala fault system In this area, as in the Deeside area to the north, a tripartite division into basal sandstone, a mudstone group ('Holywell Shales') and the Gwespyr Sandstone is still valid.

The basal sandstone group (estimated to be up to 260 m thick) comprises massively bedded quartzitic sandstones with some subsidiary mudstones and cherts. It occupies the northern part of Hope Mountain and much of the poorly exposed ground west and southwest of Llanfynydd. The overlying mudstone group (c.200 m thick) is very poorly exposed; it includes grey and black mudstones and shales intercalated with thin quartzose sandstones. Its depositional environment was fluvio-deltaic with periodic marine incursions. The Gwespyr Sandstone (c.60 m thick) is a feldspathic sandstone, in contrast to the quartzitic basal sandstones and the sandstones of the underlying Minera Formation. As such it is similar to the typical feldspathic sandstones of the overlying Coal Measures.

Halkyn Formation — south of Bala fault system A tripartite division of the formation has also been made in this area; the main difference from the sequence further north is that the basal sandstone group now occupies some 75-90% of the total thickness of the formation, with the mudstone group correspondingly reduced in significance. The basal sandstone group is well exposed in quarries along the southern side of the Nant y Ffrith from Bwlchgwyn to Glascoed; elsewhere exposure of all three divisions is generally poor.

The basal sandstone group is some 260 m thick in the north, thickening southwards to about 360 m within the study area. It comprises massive-bedded fine- to medium-grained quartzitic sandstones, with some thin beds of quartz conglomerate, intercalated with cherts, 'cherty shales' and mudstones. The cherts and 'cherty shales' are completely or partially silicified mudstones and siltstones.

The overlying mudstone group is c.30 m thick in the north, thinning southwards to c.12 m. It consists of grey and black mudstones with thin interbedded quartzitic sandstones.

The Gwespyr Sandstone (Aqueduct Grit) is up to 50 m thick in the north, decreasing southwards to c.12 m. It is a feldspathic sandstone varying from fine- to coarse-grained, and locally pebbly especially towards the base. The change in character from the quartzitic sandstones of the main body of the Halkyn Formation and the underlying Minera Formation to the feldspathic nature of the Gwespyr Sandstone and the overlying Coal Measure sandstones coincides with a change in the direction of their derivation; the quartzitic sandstones were derived from the south, whereas the younger feldspathic sandstones were derived from the north-east (Ramsbottom, 1974).

The mode of formation of the cherts and cherty shale is problematical. The main point at issue is whether the chert formed as a silica gel on the sea floor or originated by the replacement of existing strata. The evidence here, and in the Deeside area to the north (Campbell and Hains, 1988) suggests that replacement is an important factor and that much of the process of silicification occurred soon after deposition of the strata while they were still plastic. There is local interbedding of chert with siltstone and mudstone, suggesting that the chertified strata were likely to have been siltstones and mudstones prior to their silicification. Palaeontological evidence from the Halkyn area, Deeside, suggests that they were deposited in a low salinity, low energy, possibly lagoonal environment.

Coal Measures (Westphalian)

In the British Isles it is common practice to subdivide the Coal Measures in terms of the biostratigraphy (i.e. fossil content) rather than lithostratigraphy (variation of rock type). Thus, elements of the sequence are referred to as Westphalian A,B,C and D. This is a questionable method of depicting stratigraphy within what is otherwise a lithostratigraphic context, and in this report the term Bettisfield Formation (from Bettisfield Colliery, Bagillt, Deeside) has been used as a lithostratigraphic name for the Productive Coal Measures (the 'Grey Measures' of Calver and Smith, 1974). Its base is defined at the top of the Gwespyr Sandstone. This usually lies a few metres below the Subcrenatum Marine Band which marks the base of the Westphalian. Its upper limit is marked by the incoming of the red beds of the Ruabon Marl Formation.

The study area includes the southern part of the 'Flintshire Coalfield' around Leeswood, and the northern part of the 'Denbighshire Coalfield', the two areas separated by the Bala fault system. There are some differences in the sequences within the two areas which are shown on Figure 13. The most recent accounts of the North Wales Coalfields are those of Magraw and Calver (1960) and Calver and Smith (1974). The earlier accounts of Wedd and King (1924) and Wedd, Smith and

Wills (1928) provide important detail. The Coal Measures are divided into four lithostratigraphic formations within the study area; the Bettisfield Formation ('Grey Measures' of Calver and Smith (1974)) at the base is succeeded by the Ruabon Marl Formation, Coed-yr-Allt Formation and Erbistock Formation which together make up the 'Red Measures'. Workable coal seams are present only in the Bettisfield Formation. Coal Measures occupy the greater part of the study area (Figure 7). In general, exposure is very poor, mainly due to the considerable cover of superficial deposits, and most information derives from boreholes, mine-shafts and underground workings.

Bettisfield Formation (Productive Coal Measures) — general This formation consists of cyclic sedimentary sequences which ideally comprise: basal grey and dark grey mudstones, followed by siltstones; a yellowish brown, feldspathic, cross-bedded sandstone; a seatearth (fossil soil), and coal. The coal is then succeeded by the mudstone at the base of the next cycle. Mudstone is the dominant lithology of the cycles. Some bands of dark grey mudstone, which usually occur immediately above the coals, contain marine fossils including stratigraphically diagnostic goniatites. Non-marine bivalves are also used in correlation.

The cyclicity of the sediments demonstrates a systematic pattern of subsidence and infill of the basin within which they accumulated. The overall sedimentary regime was of fluvio-deltaic sedimentation in shallow brackish water with occasional marine influxes. The sandstones were deposited both by sheet-floods and by migrating channels. The coals represent condensed vegetation which accumulated in stagnant swampy conditions, whereas the seatearths which underlie them reflect soils in which vegetation flourished, but without accumulating as a coal.

The Bettisfield Formation is c.510-520 m thick in the 'Denbighshire Coalfield' and c.405 m thick in the 'Flintshire Coalfield' (Leeswood area), north of the Bala fault system, where the topmost beds are not preserved. The strata of the Bettisfield Formation dip steadily eastwards under the overlying 'Red Measures'. Most of the more recent deep mining in the Coalfield, from collieries such as Bersham, Gresford and Llay Main, was beneath this cover, often at considerable depth.

A correlation of the principal coal seams within the area is given in Figure 13.

The detailed succession in the Bettisfield Formation will be described in two parts: firstly, the measures up to the Hollin coal, in which the sequence is similar in both coalfields and secondly, the measures above the Hollin coal in which there are significant differences between the two areas.

Bettisfield Formation — measures up to the Hollin coal The marine bands commonly present in the lower part of the British Coal Measures are poorly represented in this area. The Subcrenatum Marine Band, marking the base of Westphalian A, has been recorded in both coalfields, though not within the study area. The only proven marine horizon within the study area is the Llay (Vanderbecki) Marine Band which marks the base of Westphalian B.

The thickness of the beds up to the Hollin coal varies from 240 to 260 m. The principal coal seams, in ascending order, are the Chwarelau, Llwyneinion Half-Yard, Premier, Ruabon Yard, Nant, Nine Foot, Fireclay Group (a variable group of seams which includes the Firedamp, Half Yard and

Stone), Red, Crown, Lower Bench, Main, Black Bed, Quaker, Crank and Hollin. The Premier, Nant, Nine Foot and Hollin are commonly split. The thickest of the seams are the Premier (0.66-1.67 m), Main (1.82-4.55 m), Quaker (1.07-2.05 m) and Hollin (0.93-3.00 m). The Nant (up to 3.40 m) and Nine Foot (up to 2.16 m) are more variable in thickness. The Main is consistently the thickest seam within the Bettisfield Formation. Sandstones are commonly developed above the Premier, Ruabon Yard and Main seams, that above the Main being known as the Main Rock.

Bettisfield Formation—measures above the Hollin coal In this part of the sequence there are major differences between the two coalfields. In the 'Denbighshire Coalfield' several marine horizons have been recorded, but none is known from the Leeswood district. Those in the 'Denbighshire' area are, in ascending order: the Powell (Maltby) Marine Band above the Powell seam; the Gardden Lodge (Clown) above the Drowsell coal; the Lower Stinking (Haughton) above the Lower Stinking seam; the Warras (Aegiranum) above the Warras coal, marking the base of Westphalian C, and the Ty Cerrig (Edmondia) above the Upper Stinking coal. Marine Band names in brackets are the standard terminology used in all the British Coalfields.

The thickness of the strata in the 'Denbighshire Coalfield' ranges from 230 to 265 m; in the Leeswood area, where the succession is incomplete, 145 m of beds are preserved.

The main coal seams of the 'Denbighshire Coalfield' are, in ascending order, the Powell, Drowsell, Lower Stinking, John O'Gate, Warras, Cannel, Upper Stinking, Gwersyllt Little and the Bersham Yard Group (a variable group of up to seven coals, denoted by the Greek letters Gamma to Alpha). The Upper Stinking, Beta and Alpha seams are usually split. The thickest of the seams are the Powell (0.51-1.22 m), Drowsell (0.69-2.29 m), Upper Stinking (1.60-4.00 m), Gamma (.69-1.22 m) and Beta (1.19-3.99 m). The Lower Stinking (0-2.00 m), Gwersyllt Little (0-1.47 m), Delta Bench (0.40-1.62 m) and Alpha (0-1.88 m) are more variable in thickness. A thick sandstone, the Cefn Rock (6-45 m), and other sandstone beds, occur between the Gwersyllt Little seam and the Bersham Yard Group.

In contrast there are only four significant seams within the Leeswood area, namely the Powell (0.61-1.35 m), Tryddyn Half Yard, Pontybodkin Divided (1.31-1.80 m) and Pontybodkin Mountain. The Pontybodkin Divided is a split seam which, with the Tryddyn Half Yard, is thought to correlate with the John O'Gate of 'Denbighshire'. A thick sandstone, the Hollin Rock (17-35 m), is developed above the Powell Seam; this is at a lower horizon than the Cefn Rock of 'Denbighshire'.

Ruabon Marl Formation The Ruabon Marl Formation is the lowest of the three formations included within the 'Red Measures' of Calver and Smith (1974). It is between 120 and 160 m thick in the northern part of the study area, thickening southwards to 200 to 225 m. It comprises red, brown, purple and green mudstones, commonly mottled, and thin siltstones and sandstones, with a few thin limestones and some thin grey mudstones and thin coals. The outcrop of the Ruabon Marl Formation is almost completely drift covered, the only section being in the Hafod Clay Pit [SJ 310 454]. These sediments were probably laid down in shallower more brackish water than most of the Productive Coal Measures. Their age is poorly constrained due to a lack of fossils, but the boundary between Westphalian C and D is thought to approximate to the boundary between the Ruabon Marl Formation and the overlying Coed-yr-Allt Formation (Calver and Smith, 1974).

Coed-yr-Allt Formation In contrast to the underlying Ruabon Marl Formation, the Coed-yr-Allt Formation has its maximum thickness of about 200 m in the northeastern part of the study area. It thins westwards and southwards to some 145-150 m. It comprises grey mudstones, sandy mudstones and sandstones, with parts of the succession showing red and purple bands and mottling. It has a cyclic sequence similar to that of the Bettisfield Formation, but coals are thin and there are a few thin limestone beds. The outcrop is almost entirely drift covered, the only exposures being in the Alyn Gorge, chiefly between Wilderness Wood [SJ 333 534] and Bradley [SJ 330 542]. There are a number of mine shafts and deep boreholes which penetrate part or all of the formation (Wedd, Smith and Wills, 1928). Its depositional environment shows a partial return to that prevailing during the deposition of the Bettisfield Formation, although there was no development of thick coal seams.

Erbistock Formation The Erbistock Formation is the highest formation within the Coal Measures of the study area. As it is overlain unconformably by younger rocks its original thickness is not known; about 520 m of beds are preserved in the northeastern part of the area.

The strata are red and purple mudstones with subordinate green banding and mottling, interbedded with coloured and grey feldspathic sandstones. Some intercalated grey mudstones occur, with thin coal seams, and there are a number of thin limestone beds. The outcrop is almost entirely drift covered, with sections confined to the Alyn Gorge between Wilderness Wood [SJ 333 534] and Gresford Bridge [SJ 341 552], and also around King's Mills [SJ 348 491]. Depositional conditions resemble those obtaining during the deposition of the Ruabon Marl Formation, although the higher proportion of sandstones suggests more active erosion of a nearby land area.

Permo-Triassic

Strata of Permo-Triassic age (between 280 and 210 million years old) overlie the Carboniferous rocks with marked angular unconformity. They occupy the eastern part of the study area (Figure 7) and their outcrop is completely covered by thick drift deposits on the edge of the flat Cheshire Plain. The lithology of the rocks is known from boreholes and from a limited number of sections in adjoining areas (Campbell and Hains, 1988; Earp and Taylor, 1986; Poole and Whiteman, 1966).

Two formations are present within the study area; the Kinnerton Sandstone Formation (formerly the Lower Mottled Sandstone) is overlain by the Chester Pebble Beds Formation (formerly the Bunter Pebble Beds).

Kinnerton Sandstone Formation Some 400 m of strata assigned to this formation are thought to be present in the northeastern part of the area. It seems to thin to the south as only about 300 m appear to be present in the south-east, beneath the Chester Pebble Beds. The Kinnerton Sandstone Formation comprises brownish red and yellow, cross-bedded, fine- to medium-grained sandstones; the beds were deposited by predominantly aeolian processes in a desert environment.

Chester Pebble Beds Formation The Chester Pebble Beds Formation is only present in the extreme southeastern corner of the study area, east and north-east of Bangor-is-y-coed. About 140 m of beds are present within the area. They comprise reddish brown, cross-bedded, medium- to coarse-grained sandstones, usually with abundant rounded pebbles; the pebbles, mainly of quartzite, occur scattered throughout the rock, or in lenses. They were laid down by northward flowing streams in the lower reaches of a continental drainage complex.

Structure

The most significant structural feature is the ENE trending Bala fault system which traverses the northern part of the Carboniferous outcrop (Figure 7). It has a long and complex history and may have been initiated in Precambrian times (a minimum of 600 million years ago) (Fitches and Campbell, 1987). Its most obvious effect in north-east Wales is the sinistral displacement of the main Carboniferous Limestone (Dinantian) outcrop by some 7 km; in detail, however, it is more complex and George (1974) has postulated that the decrease in thickness of the Dinantian sequence from about 900 m to the north of the fault system to some 175 m on the southern side is due either to growth faulting or some 20 km of sinistral displacement. Additionally there are some differences in the Halkyn Formation, and considerable differences within the upper part of the Bettisfield Formation (Figure 13), either side of the fault system which may be related to it. The fault does not affect the Permo-Triassic rocks, although it can be traced by geophysical methods for some distance under the unconformable Permo-Triassic cover.

On the southern side of the fault system the Carboniferous rocks have a consistent easterly dip (see Thematic Map No. 1, horizontal section); they are unconformably overlain by the Permo-Triassic rocks which have a general, but less consistent, easterly dip. The Carboniferous rocks are affected by a number of major NNW trending normal faults (e.g. the Wrexham and Gresford faults) with subsidiary conjugate E-W faults. Towards the west of the area the trend becomes NW (e.g the northern part of the Minera Fault), and most of the mineralised faults within the Carboniferous Limestone have this trend. The major faults swing to N or NNE trending towards the south of the study area. There are very few folds, and those are only of minor significance.

The area to the north of the Bala fault system is structurally more complex. The major faults still have a NNW trend, and recent exploration for opencast coal sites has shown that there are many minor faults of similar trend. The Carboniferous Limestone and Halkyn Formation on the southern part of Hope Mountain are folded into a broad NE trending anticline, the southern part of the so-called 'Horseshoe Anticline' of Wedd and King (1924). This anticline is complicated by numerous anastomosing faults, mainly with a northerly or northwesterly trend. It is not known if this mode of faulting extends into the poorly exposed ground surrounding Hope Mountain to the east, north and west.

The dominant N-S (or NNW-SSE) and conjugate E-W normal faults were probably generated during the formation of the extensional basin in which the Carboniferous rocks were deposited. There may have been further movement along many of the faults during the end-Carboniferous (Hercynian) earth-movements. There is geophysical evidence that some of the faulting penetrates the overlying Permo-Triassic rocks, and it is possible that this may represent a reactivation of earlier faulting within the underlying Carboniferous sediments. The extensive drift cover has prevented any detailed study of structures within the Permo-Triassic rocks.

Mineralisation

The locally intense lead, zinc and copper mineralisation which occurs in the Carboniferous Limestone south of the Bala fault system was strongly influenced, and probably controlled, by the NW-SE faults. The mineralisation occurs mainly in discontinuous veins (?solution infils) along faults and joints, but it also occurs in steep pipes (probably infilled solution pipes). The chief ore is galena (lead sulphide), with sphalerite (zinc sulphide) and minor amounts of chalcopyrite (copper/iron sulphide). The main associated vein (gangue) mineral is calcite, although quartz is locally dominant at Minera. There are small amounts of zinc and lead carbonates. At Minera, galena alone is present at the north-west end of the mineralised area; towards the south-east blende becomes common and in the extreme south-east is more abundant than galena. This suggests a broad zonal arrangement of the primary minerals (Earp, 1958).

North of the study area, in the southern part of the Deeside area (Campbell and Hains, 1988), there is little mineralisation in the Carboniferous Limestone above the level of the 'Main shale'. Similar constraints appear to apply at Park Mines, south of Minera. However, at Minera itself mineralisation extends throughout the Carboniferous Limestone and into the basal part of the overlying sandstones of the Halkyn Formation. It seems likely that the large throw of the faults and the many and varied enclosed lenses of strata have tended to mask the effects of shale beds in controlling ore distribution within the limestones.

The nature and stratigraphic distribution of the ores suggest that, in the main, they were precipitated in solution voids within the limestone and particularly along pre-existing faults and joints. The stratigraphic restrictions probably reflect the optimum conditions for precipitation of the mineralising fluids (e.g pH).

Quaternary

The area was affected by several periods of glaciation during the Quaternary, but only evidence of the last glaciation (Devensian) has been preserved. Glaciation affected a post-Triassic erosion surface and accentuated existing valleys. In addition, new dissections were caused by subglacial and periglacial processes. Ice-sheets from two directions impinged on the area, one from the direction of north and central Wales (the 'Welsh' ice-sheet) and the other from the Irish Sea to the north ('Irish Sea' ice-sheet). North of Caergwrle these ice-sheets merged in the vicinity of the River Alyn, and southwards to the west of Wrexham (Ball, 1982; Dunkley, 1981; Thomas, 1985, 1989). Extensive basal tills (boulder clays) were deposited. These tills, and later glacial and fluvioglacial deposits, cover most of the central and eastern parts of the study area, and are often of considerable thickness, up to a maximum of about 100 m (see Map No. 4 for drift isopachytes).

The two different ice-sheet sources are reflected in the different clast compositions of the two till deposits. The 'Welsh' ice-sheet till comprises grey clays with clasts mainly of Lower Palaeozoic cleaved siltstones and sandstones, vein quartz and acidic volcanic rocks. The 'Irish Sea' ice-sheet till comprises reddish brown clays with abundant clasts of Carboniferous Limestone, mudstone, sandstone, chert and coal of local derivation, in addition to Triassic sediments and granitic, volcanic, metamorphic and vein quartz clasts of more distant provenance.

During the retreat stage of the ice-sheets, meltwater flowed southwards between the retreating ice margins and laid down a complex series of fluvioglacial and lacustrine deposits in the Wrexham district. There have been a number of conflicting interpretations of the mode of deposition of these sediments (Peake, 1961; Poole and Whiteman, 1961; Wilson, Mathers and Cannell, 1982; Thomas, 1985, 1989) but it is clear that the extensive sand and gravel deposits around Wrexham (the 'Wrexham Delta-terrace' of Wedd, Smith and Wills, 1928) were formed as a complex outwash fan deposited, at least partly, in or on the margins of a proglacial lake (Bangor Lake of Thomas, 1989). Lacustrine silts and clays laid down in this lake, and possibly in other transient lakes, occur to the east and north-east of Wrexham. Minor ice-sheet readvance occurred, resulting in the local interdigitation of till and fluvioglacial sand and gravel.

The retreating ice-sheets left patches of dead ice and the melting of these produced kettle holes (depressions) in the sand and gravel deposits. These were sites of small lakes and ponds and laminated clay and peat accumulated within them. In the periglacial freeze-thaw conditions of the immediate post- glacial era, glacial deposits suffered downslope mass-movement by solifluction processes producing head deposits. Landslip also occurred at this time, both in bedrock and superficial deposits, and it persists to the present day. Some of the major pre-glacial valleys, and particularly parts of the Alyn and Dee valleys, were largely infilled by glacial deposits. Flood conditions continue to infill the valleys with alluvium.

ANNEX B DATA SOURCES USED IN THE REPORT

British Geological Survey (BGS) archival maps and data

The primary survey of the northern part of the study area was carried out, at the 1:10 560 scale, by Strahan and De Rance (1879-1885). The remainder of the area was first surveyed, and the northern part partially revised, by King, Lamplugh, MacAlister, Thomas, Wedd and Wills in 1910-1913. The eastern margin of the area was revised by Poole in 1956. The field-slips relating to all these surveys are held at the Aberystwyth Office of BGS. Descriptive memoirs for all these surveys were produced (Strahan, 1890; Wedd and King, 1924; Wedd, Smith and Wills, 1927, 1928; Poole and Whiteman, 1966; Earp and Taylor 1986), and maps published at 1:63 360 scale. In addition, maps of the coalfield areas were published at 1:10 560 scale as a result of the 1910-1913 survey. The metalliferous deposits of the area were described in a Mineral Resources Memoir (Smith, 1921). Further updating of part of the area was undertaken by Lowe, Reedman and Tappin in 1977-1980, and the 1:10 560 sheet SJ 24 NE was published in 1982. The sand and gravel reserves of the area were described in two Mineral Assessment Reports (Dunkley, 1981; Ball, 1982). Extensive non-confidential and confidential borehole records were held prior to the present project at the Aberystwyth Office of BGS, as were some geotechnical reports and plans and cross-sections relating to metalliferous mining.

Field Survey

Information was obtained from a detailed field survey of the Hope Mountain area by Drs Davies and Wilson in 1989, and from a photo-interpretation with limited field checking for the remainder of the study area. The Hope Mountain area had not been surveyed since 1880, and the complex stratigraphy and structure of the rocks required a complete re-interpretation. The observations made during this survey were recorded directly on to 1:10 000 field-slips. Standard BGS mapping techniques were used during the field survey. These include systematic examination of all exposures of rock, with detailed descriptions and measured sections recorded where appropriate. Most topographic features greater than approximately 1 metre in elevation were systematically recorded to assist in interpretation in areas of limited rock exposures. Some fossil identifications were carried out by Dr N J Riley of the Keyworth Office of BGS to help elucidate the stratigraphy of the area. In other areas, black and white air photographs (approximate scale 1:10 000) were examined, mainly to determine areas of made ground, backfill and landslip. These areas were then checked in the field. The photographs were examined at the Clwyd County Council offices in Mold where they hold a complete stereoscopic cover of the study area dating from 1984-5.

British Coal Databases

A number of databases are held by British Coal. Borehole data abandonment plans and other data obtained from the Opencast Executive was used to derive coal seam crops and other information but the primary data remains confidential. A copy of the British Coal Shaft Register was obtained; from this register, geological fieldslips and other sources, some 1350 shafts and adits have been located with varying degrees of accuracy. Seam plan information was collated from the Coal

Commission plans, and other plans held by British Coal, Staffordshire House, Berry Hill Road, Stoke-on-Trent ST4 2NH. A synthesis of this seam plan data is held on maps at 1:10 560 scale at the Aberystwyth Office of BGS, and in a computer database at Keyworth.

Site Investigation Data

Site investigation information for civil engineering projects was obtained from many bodies including the Welsh Office, Clwyd County Council, Alyn and Deeside District Council, Wrexham Maelor Borough Council, the Welsh Development Agency and a number of geotechnical consultants. This information comprises borehole data and trial pits, with, in 575 cases, details of engineering properties, and in some instances full geotechnical and other reports. Most of the boreholes were drilled by shell and auger rigs and are less than 25 m in depth, and many are restricted to the unconsolidated deposits. The distribution of borehole sites is very uneven, with particular concentrations in industrial estates and along major road improvement schemes. In total, including British Coal borehole data, records from approximately 4200 non-confidential and confidential boreholes were considered during the project. Details of all the boreholes, including summaries of the geological data, have been entered into a computer database (Annex D). Geotechnical data has been entered into a separate, but compatible, database. These databases are held at the BGS Headquarters at Keyworth. The paper copies of the borehole logs are held at the Aberystwyth Office of BGS where the non-confidential logs can be consulted.

Hydrogeological Data

The National Rivers Authority and the Welsh Water Authority provided information on water wells and boreholes, water abstraction and quality, chemical analyses of water and on landfill sites.

Scientific Publications

Various publications relevant to the area are available in the scientific literature. These deal particularly with aspects of the stratigraphy of the Carboniferous Limestone sequence and with the nature and interpretation of superficial deposits within the area. They are referred to where appropriate within the report and full details are given in the reference list. The references are available in the libraries of the British Geological Survey at Aberystwyth and Keyworth. Other useful reference centres are: the London Information Office, British Geological Survey, Geological Museum, Exhibition Road, London SW7 2DE; the Department of Geology, Jane Herdman Laboratories, University of Liverpool, PO Box 47, Liverpool; and for historical information with reference to mining and quarrying, the Clwyd Records Office, Clwyd County Council, Hawarden.

Using all the sources listed above, geological maps at the scale of 1 10 000 were prepared. Each map delineates both lithological and structural variations in the bedrock geology and the nature and distribution of superficial deposits (drift). In addition the sites of selected shafts, adits and non-confidential boreholes were plotted. Each base map has a generalised vertical section with general descriptions of the constituent geological formations. The geological linework has been digitised and other information entered into a computer database so that the 1:10 000 geological maps can be computer generated as required. This database, together with those containing information on mine plans, boreholes (including geotechnical data), shafts, adits and other point data such as the position of quarries, pits and kettleholes, has been entered into a Geographic Information System (GIS). A digital terrain model has been produced and also entered into the GIS. Selected elements of these various databases have been combined within the GIS to generate the thematic maps.

ANNEX C THE GEOTECHNICAL DATABASE

The classification of the geological formations into groups or units of similar engineering properties was carried out using geotechnical data extracted from site investigation reports on sites located in, or within 2 km of, the study area. Data was abstracted, coded onto a specially designed form and keyed into a computer database using an IBM compatible microcomputer and commercially available software. The geotechnical database is maintained as a separate entity. However, all the boreholes for which data are available are also held within the main borehole database, and each borehole has the same accession number in each data set. Geotechnical data were obtained for 4979 individual samples from 575 boreholes.

The results of the following geotechnical tests and measurements (laboratory and in situ) were abstracted and entered into the database:

1 Standard penetration test (SPT).

2 Moisture content.

3 Liquid limit.

4 Plastic limit.

5 Bulk density.

6 Dry density.

7 Specific gravity.

8 Particle size analysis (PSA).

9 Triaxial compression (drained and undrained).

10 Consolidation.

11 Compaction.

12 California bearing ratio (CBR).

13 pH. (acidity/alkalinity)

14 Sulphate content (of soil and groundwater).

15 Rock quality designation (RQD).

A brief description of the tests and their applications is given below. The following should be consulted for further information: British Standard 1377, (1975) and British Standard 5930, (1981).

The *standard penetration test* (SPT) is a dynamic test carried out at intervals during the drilling of a borehole, 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 *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. It is a basic soil property and influences soil behaviour with regard to compaction, plasticity, consolidation and shear strength characteristics. As moisture is removed from a fine-grained soil it passes through a series of states, that is 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'.

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

The *liquid limit* (LL) is the minimum moisture content at which the soil flows under its own weight. The range of moisture content over which the soil is plastic is known as the *plasticity index* (PI), such that 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 amount and proportions of silt, fine clay 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 charts also give an indication of soil strength and compressibility.

Density of a soil, that is the mass per unit volume, 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. 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.

The *specific gravity* of a soil is the ratio of the weight of dry solids to the weight of an equal volume of water (ie the weight of water displaced by the solids). It is, therefore, a dimensionless parameter. 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.

Particle size distribution is used for classifying soil in engineering terms. 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 bulk test sample.

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. The test may be carried out with the sample either drained or undrained and the type of test will depend upon the site conditions and type of engineering works being undertaken.

Graphical interpretation of the results enables the shear strength of the soil to be determined in terms of its cohesive and frictional components: undrained (apparent) cohesion, *C*, and angle of shearing resistance (internal friction), *U*.

If 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 *coefficient of volume compressibility* Mv (m^2/MN), is a measure of the amount of volume decrease that will take place for a given increase in stress. The *coefficient of consolidation*, Cv (m^2/year), is a measure of the rate at which the volume change will take place for a given increase in stress. The results of consolidation tests give Mv and Cv at a number of increasing loads. To enable this range of values to be used in the database the ranges are converted to classes using the tables which have been taken from Head (1982) and Lambe and Whitman (1979). The assignment to a class is mainly based on the mid-range values obtained during progressive testing.

Coefficient of volume compressibility (Mv)

m^2/MN	Class	Description of compressibility
>1.5	5	Very High
0.3 – 1.5	4	High
0.1 – 0.3	3	Medium
0.05 – 0.1	2	Low
<0.05	1	Very Low

Coefficient of consolidation (Cv)

m^2/yr	Class
<0.1	1
0.1 – 1	2
1 – 10	3
10 – 100	4
>100	5

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 pressure) to take place prior to successive load stages.

The *compaction* test determines the *'optimum' moisture content* at which a soil may be compacted to its maximum dry density. 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. 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.

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 = (Measured force) / ('Standard Force')

The CBR value of recompacted soil is very sensitive to variations in moisture content and dry density. 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.

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 metal work.

It is also important that the *sulphate content* of groundwater and soil is known, as ordinary Portland cement deteriorates in the presence of sulphate. Building Research Establishment Digest No. 250 (1981) discusses the factors responsible for sulphate attack on concrete below ground level, and recommends what can be done, by suitable selection of cement type and concrete quality, to resist attack by naturally occurring sulphates. Part of the appropriate table is reproduced below, but the document should be consulted for further information.

Allocation to sulphate class in concentrations of sulphate expressed as SO_3

Concentrations of sulphates expressed as SO_3

		in soil	in groundwater
Class	Total SO_3 (%)	SO_3 in 2:1 water: soil extract g/l	g/l
1	<0.2	<1.0	<0.3
2	0.2 to 0.5	1.0 to 1.9	0.3 to 1.2
3	0.5 to 1.0	1.9 to 3.1	1.2 to 2.5
4	1.0 to 2.0	3.1 to 5.6	2.5 to 5.0
5	>2	>5.6	>5.0

Rock quality designation (RQD) was introduced to give an indication of rock quality in relation to the degree of fracturing from drill cores. It is defined as a sum of the core sticks in excess of 100 mm in length expressed as a percentage of the total length of core drilled. 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. For further information see Deere (1964).

ANNEX D THE BOREHOLE DATABASE

BGS holds an extensive collection of paper records which describe the strata encountered during the sinking of boreholes, mineshafts and trial pits. These records represent a major source of factual data for future geological investigations and interpretations within the study area. The paper borehole record is considered to be the authoritative primary record and there has been no attempt to replicate it on the computer. A computerised database for the project area was seen as a way of utilising the data held in the paper archive to maximum effect by allowing rapid and flexible retrieval of a wide range of information.

All borehole and shaft records in the project area have been coded following a format which has been developed within BGS. This work has resulted in the establishment of a simple system by which borehole information can be assigned to two tables of data, on the basis of the following criteria:

All data which describes a feature of the borehole itself, for example, its name, its location by National grid reference, the date it was drilled, height above (or below) sea level.

All information relating to samples taken from point depths below the surface for that borehole.

A complete list of fields in each of these tables within the borehole database is given below.

The data is currently held in an Oracle relational database management system running on a VAX 8560 computer at BGS Keyworth. It can be interrogated by menu or specifically by using a query language (SQL). It may be used as an index to available records or for detailed geological analysis. Retrieved data may be manipulated and displayed using a number of statistical and graphic application packages and it is possible to automatically produce graphic vertical sections (Figure 10), scatter plots, contour maps and three-dimensional diagrams. Several elements within the thematic maps were produced by retrievals from the database.

List of fields in the BGS Keyworth borehole database

Index table		**Lithological table**
OS 1:10 000 sheet number*	Reliability	OS 1:10 000 sheet number*
Accession number and suffix*	Start point	Accession number and suffix*
National grid reference and accuracy	Inclination	Depth
Borehole name	Drilling date	Lithology
Comments	Geologist	Base of bed
Surface level and accuracy	Drilling method	Reliability
Confidentiality	Borehole diameter	Workings
Purpose	Consulting engineer	Comments
Originator	Drilling contractor	
	Water strike	

* "the primary key index"

ANNEX E GLOSSARY

Alluvium Detrital material transported by a river and deposited along its floodplain

Anticline Rocks folded in the form of an arch

Aquifer A body of rock that contains sufficient saturated permeable material to conduct *Groundwater* and to yield economically significant quantities of groundwater to wells, boreholes and springs

Argillaceous A deposit containing an appreciable amount of clay

Artesian head The hydrostatic head of an artesian *Aquifer*, or of the water in the aquifer

Artesian pressure Hydrostatic pressure of artesian water, or height above land surface of a column of water that would be supported by the pressure

Basin A depression in which sediments accumulate

Bedding The arrangement of a sedimentary rock in beds or layers of varying thickness and character

Bedrock Geological strata at surface and below *Superficial deposits*

Bioclastic A sediment comprising fragments of *Skeletal* material

Bivalve A (fossil) mollusc with two shells which are symmetrical with respect to each other

Brachiopod A marine animal (fossil) with two symmetrical shells

Buried channel An old channel concealed by *Drift* deposits

Calcareous A deposit that contains calcium carbonate

Calcite A common rock-forming mineral, $CaCO_3$

Calcite mudstone A *Limestone* similar to a *Wackestone*, but in which the carbonate grain content must be less than 10% of the whole rock

Calcspar Coarsely cystalline calcite, usually in veins

Carbonaceous A deposit that contains organic matter

Cementstone A fine-grained *Calcareous siltstone* or *Limestone*

Chert A rock comprising very fine-grained quartz

Clast An individual grain or rock fragment

Cleaved Pertaining to a rock fabric imposed by compression

Cohesive A sticky *Soil* like clayey silt

Conglomerate A coarse-grained sedimentary rock with average clast size greater than 4 mm

Correlation The process by which *Stratigraphic* units in two or more areas are demonstrated to be temporally equivalent

Crinoid A marine organism (fossil) with a structure comprising discs of calcite

Cross-bedding Structure in sedimentary rocks comprising intersecting *Bedding* planes

Cyclicity A repeated sequence of beds or rock units

Debris flow A depositional mechanism akin to a mud slide

Dip The angle of inclination of a surface (e.g. *Bedding*) in relation to the horizontal

Disharmonic Relating to folds which differ in form with respect to one another

Distal Distant from

Drift A general term for all superficial unconsolidated rock debris of Quaternary age distinguished from solid bedrock

Facies change A change in the internal characteristics of a rock unit

Fault A surface or zone of rock fracture along which displacement has occurred; movement may either be vertical (normal or reversed), lateral (strike-slip) or a combination of the two

Feldspathic A deposit that contains the mineral feldspar in significant quantity

Field-slip The base map on which geological observations and comments are recorded

Fireclay a *Seatearth* comprising quartzose clay, and capable of withstanding high temperature without deforming

Formation The fundamental unit of subdivision of a rock sequence which is unified in internal characteristics and differs with respect to adjacent formations

Geotechnical The application of scientific methods and engineering principles to the acquisition, interpretation, and use of knowledge of materials of the Earth's crust to the solution of civil engineering problems

Goniatite A fossil mollusc with a shell of spiral form

Graben A sequence of strata between two *Faults*, that is lowered relative to adjacent strata

Grainstone A *Limestone* where the individual grains of carbonate are in direct contact (grain-supported) and fine-grained carbonate mud is minimal

Gravel An unconsolidated accumulation of rounded grains of average grain size greater than 4 mm

Groundwater Water contained in the soil or rock below the water-table

Hardness A property of water causing formation of an insoluble residue

Horizontal section An interpretive diagram displaying the structure and sequence of strata at depth

Horst A sequence of strata between two *Faults*, that is raised relative to adjacent strata

Igneous Rock which was originally molten

Induration A process by which a soft sediment becomes a hard rock (hence *Indurated*)

Isopachyte A line joining points of equal bed or deposit thickness

Karstic Relating to irregular topography of a limestone surface by its dissolution

Kettle hole A steep-sided depression in glacial deposits, usually containing clays and peat laid down in a lake or swamp

Lacustrine Pertaining to a lake

Laminated A very fine type of *Bedding* less than 1 mm thick

Limestone A sedimentary rock mainly comprising calcium carbonate

Lithological Pertaining to rocks

Lithostratigraphical Pertaining to the classification of rocks on the basis of their physical characters

Mature (*of Sandstone*) Pertaining to a predominance of well rounded and spherical grains

Member A distinctive unit of strata within a *Formation*

Metamorphic Pertaining to rocks which have been affected by high temperature and/or pressure resulting in changes in their mineral constituents

Mudstone A sedimentary rock comprising very fine-grained particles

Nodule (phosphatic, ironstone, carbonate) A small body of mineral or mineral aggregate, often rounded or ellipsoidal in profile

Overconsolidated Clay that still retains some of the imposed stress from a previous greater overburden

Packstone A *Limestone* which is generally grain-supported (see *Grainstone*) but with significant fine-grained carbonate mud matrix, in some instances resulting in separation of the carbonate grains

Palaeontological Pertaining to the study of fossil plants and animals

Particle size distribution The percentage of particles in each size fraction of a sample of soil, sediment or rock; the result of particle size analyses

Pelloid (Peloid) A grain formed of fine-grained *Calcareous* material irrespective of size or origin

Periglacial Said of the processes occurring in the region adjacent to glaciers and ice sheets

Peritidal A sedimentary environment within or near to the tidal range

Permeability The property or capacity of a rock, sediment or soil for transmitting a fluid

pH The measure of the acidity or alkalinity of a solution

Pipe A cavity, usually in calcareous rocks, commonly filled with clay, sand or gravel

Platform (as in carbonate) Pertaining to a very gently sloping sea bed, with little topography

Porcellanous Pertaining to a very fine-grained calcareous sediment resembling unglazed porcelain

Porosity The property of a rock, soil or other material containing interstices; it is commonly expressed as a percentage of the bulk volume of material occupied by interstices, whether isolated or connected

Proglacial The environment in front of a glacial ice sheet

Prograding Relating to sediments laid down as a deposit which builds out in front of the source of the sediments

Pseudobrecciated Pertaining to a texture in limestone resembling a fragmental rock, but is produced by alteration of the limestone

Quartzitic A deposit mainly comprising quartz

Quartzose A deposit containing quartz

Rock (Engineering) A naturally found material with a uniaxial compressive strength over a certain minimum value (usually taken as 1 MN/m^2), and composed of mineral grains

Rockhead The interface between unconsolidated *Superficial deposits* and *Bedrock* (and usually taken as the base of the weathering profile of the bedrock)

Running Mass flow of non-cohesive *Sand* due to high water content

Sand(stone) A sediment (consolidated) comprising grains between 0.063 and 4 mm in average size

Seatearth A unit, generally of clay, that underlies a coal and represents the fossil soil on which the vegetation grew

Shale A *Mudstone* with bedding parallel fissility

Sheet-sand A unit of *Sandstone* of wide areal extent and limited thickness variation

Silt(stone) A sediment (consolidated) comprising grains between 0.063 and 0.004 mm in average size

Skeletal Carbonate fragments of organic origin

Slumped Pertaining to sediment disrupted on the sea floor due to gravitational collapse

Soil (Engineering) All material formed from aggregates of rock particles which can be separated by gentle mechanical means and excavated without blasting

Solid *Bedrock* geology (excluding *Drift* deposits)

Solifluction A process involving the slow downslope movement of superficial material as a result of the alternate freezing and thawing of the contained water

Standard The fair copy of the geological map (scale 1:10 000 or 10 560)

Stratigraphic Pertaining to the study and classification of the sequence of rock strata in the Earth's crust

Strike The orientation of a horizontal line drawn on an inclined surface (e.g. *Bedding*)

Stylolites Irregular surfaces within limestone due to dissolution, and with insoluble residue preserved along the contact

Subartesian Said of confined *Groundwater* that is under sufficient pressure to rise above the water-table, but not to the land surface

Superficial deposits Unconsolidated glacial and postglacial sediments

Swallow holes Closed depressions or dolines into which all or part of a stream disappears underground

Syncline Rocks folded in the form of an inverted arch

Tectonic Pertaining to forces which deform or disrupt strata

Trace fossil A sedimentary structure comprising the fossilised burrow or track of a marine organism

Transmissibility In an *Aquifer*, the rate of flow of water through each vertical strip of the aquifer having a height equal to the thickness of the aquifer and under a unit hydraulic gradient

Turbidite The sediments deposited from a *Turbidity current*

Turbidity current A turbulent mixture of sediment and water which flows on the sea floor under the influence of gravity

Unconformity A break in the sedimentary sequence with strata of a particular age absent and possibly an angular relationship between the strata of different ages

Vein A mineral infilling of a fault or fracture in a rock, and usually sheet-like

Vertical Section A diagrammatic representation of vertical variations in a sequence of strata

Vibroreplacement A technique for improving the load-bearing characteristics of soft, cohesive *Soils*. Depending upon its undrained shear strength (see Annex C), the soil is either displaced radially by use of a vibrating probe, or removed to the surface by washing out with a vibrating probe with water jetting. The hole is infilled, in stages, with well-graded 75-100 mm angular stone which is compacted within the vibrator. The stone columns provide vertical support for overlying structures, and also function as vertical drains.

Wackestone A *Limestone* where the fine-grained carbonate mud matrix is predominant and individual carbonate grains (which must comprise more than 10% of the rock) are rarely in contact with one another (i.e. the grains are matrix-supported)

Well sorted Pertaining to a sedimentary rock comprising particles all approximately of the same size

Zonal Pertaining to a subdivision (zone) of strata based on its fossil content