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The physical properties of minor aquifers in England and Wales

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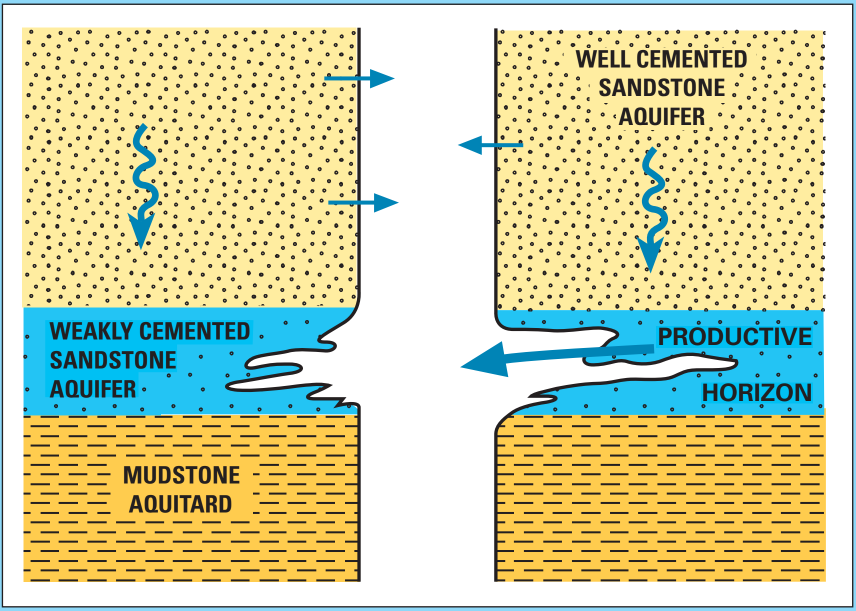

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The physical properties of minor aquifers in England and Wales

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Foreword

This report and its associated compact disk are the published products of a three year collaborative study between the British Geological Survey (BGS) and the Environment Agency. It follows on from a similar project collating the aquifer properties of the six major aquifer systems of England and Wales. The latter was published in 1997 (as BGS Technical Report WD/97/34 and Environment Agency R&D Publication 8 respectively), and this report forms a natural complement by compiling and reviewing similar information for the many minor (but locally important) aquifers of England and Wales. Both the BGS and the Environment Agency are national organisations with interests in a broad survey of aquifer properties data. For the Environment Agency the incentives for the project have been the need to provide a sound scientific basis for the Groundwater Protection Zones which are an important tool of the National Groundwater Protection Policy, and desire for a better understanding of already widely-utilised groundwater resources. For the BGS, the study was seen as helping to satisfy its charter, in which the dissemination of information is an important role for the Survey.

The project has been undertaken by BGS staff, with the assistance of Environment Agency personnel in such matters as the provision of data, the contribution of expert opinion and the review of the report.

Project staff have attempted to ensure that information contained in this report is as accurate as possible. However neither the BGS nor the Environment Agency can be held liable for any inaccuracies or omissions in the report, its appendices or the accompanying electronic media.

Numerous authors have contributed to the study. The authors principally responsible for each of the chapters are listed below.

Introduction
B L Morris

Information collection and use
B L Morris

Neogene and Quaternary minor aquifers of East Anglia: the Crag
H K Jones

Palaeogene minor aquifers of the London and Hampshire basins
H K Jones, L M Coleby, B L Morris

Cretaceous minor aquifers
H K Jones, L M Coleby, V K Robinson

Jurassic minor aquifers
M A Lewis

Permian and Triassic minor aquifers
C S Cheney, L M Coleby

Carboniferous minor aquifers
C S Cheney, A M MacDonald

Devonian minor aquifers
B L Morris

Pre-Devonian and igneous minor aquifers
C S Cheney

Other members of the team have provided geological overviews for the various chapters, constructed the database which underpins this report, conducted analysis using GIS, provided the statistical material used for interpretative and illustrative purposes in the report, and undertaken editorial tasks.

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P D Merrin

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Anglian Region
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North East Region
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E Parry, P Stewart

Southern Region
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South Western Region
L Careless, S Hartley, P Johnston,

Thames Region
V Robinson, A Attwood, N Hawkes

Welsh Region
W Davis, S Neale

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Glossary

Advection Mass transport due simply to the flow of water in which the mass is dissolved.

Arithmetic mean The sum of all the values of *n* numbers divided by *n*.

Bulk hydraulic conductivity This term is used in the report to represent the average hydraulic conductivity of a section of aquifer, and is made up of matrix and fracture components.

Chronostratigraphy Stratigraphy that interprets geological history by determining the age and time sequence of the Earth's rock strata.

Coefficient of determination R^2 This is a measure of how well a regression model describes a data set. The closer to 1 the better the independent variable predicts the dependent variable. R^2 equals 0 when the values of the independent variable do not allow any prediction of the dependent variable from the independent variable.

Connate Originating at the same time as adjacent material.

Conjugate joints The sets of joints which are related in deformational origin, usually compression.

Cumulative frequency distribution A curve drawn to represent the percentage of occurrences of a number of observations of a variable less and greater than any given value for an entire sample.

d_{50} One of the measures of sediment particle size used to characterise a sediment. It is the particle size from a sieving process where 50% of the material is finer and 50% of the material is coarser.

Drawdown The reduction of the pressure head in an aquifer as the result of the withdrawal of free water.

Effluent river conditions A reach of a river is effluent with respect to groundwater if the river gains water from the underlying aquifer.

Fracture The term fracture is used in the report to refer to a parting in a rock. The term does not imply any particular orientation or origin, except that of brittle failure. Thus joints and faults are fractures, but a fracture is only referred to as a joint or fault if the relevant mode of formation is known. The term fissure is commonly used by hydrogeologists but its meaning is imprecise and is not used in the report. Where fractures are thought to have been enlarged by solution they are described as such.

Geometric mean The *n*th root of the product of the values of *n* positive numbers.

Hydraulic conductivity The hydraulic conductivity, K of a material is the constant of proportionality in Darcy's Law, which relates the flow rate of a liquid through a material to the hydraulic gradient (see Chapter 2 for further discussion). It is usually expressed in m/d.

Influent river conditions A reach of a river is influent with respect to groundwater if it contributes water to the zone of saturation of an underlying aquifer.

Karst Used to refer to a limestone region characterised by a dry and barren surface and underground drainage via channels, with swallow holes, caves, large springs and other features. Name derived from Karst region of the Dinaric Alps, near to the Adriatic coast of former Yugoslavia.

Licensed quantity Is the volume of water, usually expressed as m^3/d, which a user is allowed to withdraw from a groundwater source under the terms of an abstraction license issued by the Environment Agency.

Lithostratigraphy Stratigraphy based only on the physical and petrographic features of rocks; the delineation and classification of strata as three-dimensional, lithologically unified bodies.

Locality As used in the database, the term refers to an area encompassing sites within 100 m of each other.

Meteoric Pertaining to water of recent atmospheric origin.

Packer testing A field method of hydraulic conductivity testing involving the use of mechanically-, pneumatically- or hydraulically-expanded packers in a borehole to isolate a section of the drilled length. The resultant separated section is then tested in a manner similar to standard pumping tests by injecting or withdrawing water over a period of time.

Permeability The term permeability, used in a general sense, refers to the capacity of a rock to transmit water. Such water may move through the rock matrix (*intergranular permeability*) or through joints, faults, cleavage or other partings (*fracture or secondary permeability*) (see Chapter 2 for further discussion).

Porosity Porosity Φ [dimensionless] is commonly defined as the ratio of the pore volume to the bulk volume of a material. Several types of porosity may be defined within this general definition (see Chapter 2 for further discussion).

Potentiometric surface An imaginary surface representing the static head of groundwater and defined by the level to which the water will rise in a well/piezometer. Replaces the earlier term *piezometric surface*.

Pressure head Hydrostatic pressure expressed as the height of a column of water that the pressure can support, expressed with reference to a specific level such as land surface. The *hydraulic head* is the height of the free surface of a body of water above a given surface or subsurface point.

Pumping test A field testing procedure to quantify aquifer properties at a site involving pumping water out of (or less commonly injecting water into) an aquifer and measuring the effect on water levels in that aquifer and sometimes in adjacent strata. There are several different procedures employed depending on the physical properties to be quantified. A *constant-rate pumping test* is conducted at a steady rate of discharge or injection; a *step-test* increases the discharge in stages to a maximum value; a *bailing test* is conducted during the drilling process, using the bailer drilling tool as a water withdrawal method.

Quartile Any one of three values dividing a frequency distribution into four classes, obtained graphically from a cumulative curve by following the 25, 50 or 75 percent line to its intersection with the curve and reading the value. The latter are *percentiles* and the *interquartile range* is the difference between the *25 percentile* and the *75 percentile* of a range.

Recharge The processes involved in the absorption and addition of water to an aquifer, usually from the surface. Recharge may be derived directly from precipitation or come from surface water in the form of river bed leakage.

Site As used in the database, the term refers to a geographical point from which data are available.

Specific capacity Q/s of a well or borehole represents the yield of a well or borehole per unit drawdown. It is expressed in this report as m^3/d/m.

Specific storage S_s of a saturated aquifer is defined as the volume of water that a unit volume of aquifer releases from storage under a unit decline in hydraulic head (see Chapter 2 for further discussion). Values are usually expressed in m^{-1}.

Specific yield S_y [dimensionless] is taken broadly to represent the storage coefficient of an unconfined aquifer (see Chapter 2 for further discussion).

Storage coefficient S [dimensionless] is the volume of water which an aquifer releases or takes into storage per unit surface area of aquifer per unit change in head. It is sometimes referred to as storativity (see Chapter 2 for further discussion).

Transmissivity Transmissivity T is the product of hydraulic conductivity and aquifer thickness, with values usually quoted as m^2/d (see Chapter 2 for further discussion).

Uniformity coefficient (d_{40}/d_{90}) A ratio used to charactertise a sediment using a plotted grain-size distribution curve. It is the 40% retained size divided by the 90% retained size.

Yield Q is the volume of water per unit of time discharged from a well or spring. Values in this report are quoted in m^3/day.

Notation with units employed in this report and in Allen et al. (1997)

A	cross-sectional area of rock perpendicular to flow [m^2]
bgl	below ground level [m]
brt	below rotary table [m]
d	day
g	acceleration due to gravity [m/d^2]
i	hydraulic gradient
k	intrinsic permeability [m^2]
K	hydraulic conductivity [m/d]
K_h	horizontal component of hydraulic conductivity [m/d]
K_v	vertical component of hydraulic conductivity [m/d]
m	metre
m^3/d	cubic metres per day
OD	Ordnance Datum
Q	flow rate [m^3/d]
Q/s	specific capacity [$m^3/d/m$]
s	drawdown [m]
S	storage coefficient
Ss	specific storage [m^{-1}]
Sy	specific yield
T	transmissivity [m^2/d]
V	rock volume [m^3]
Vp_I	interconnected pore volume in rock of volume V [m^3]
Vp_T	total pore volume in a rock of volume V [m^3]

α	aquifer compressibility
β	water compressibility
μ	dynamic viscosity
ρ_w	water density
ρ_b	dry bulk density
ϕ	porosity
ϕ_I	total interconnected porosity
ϕ_K	kinematic porosity
ϕ_T	total porosity

Summary

This report is the result of a three-year collaborative project between the British Geological Survey and the Environment Agency. The aim of the project has been to collect, collate and present information concerning the physical hydraulic properties of the minor aquifers in England and Wales. These properties include hydraulic conductivity, porosity, transmissivity and storage coefficient. In addition, specific capacity (yield per unit drawdown) values are included for many of the formations described, together with yields for those formations where aquifer properties data are sparse.

Although the parameters studied were limited in number, the study has proven to be complex for several reasons. Firstly the aquifers themselves are hydraulically complicated. They are bodies of rock, sometimes with indeterminate boundaries, which are heterogeneous either because of sedimentological factors in the case of the Cainozoic aquifers, or because of the effects of fracturing in older formations. This heterogeneity presents several problems.

Firstly, hydraulic tests on such materials often violate the classical assumptions used in the test analysis, and the complexity of the aquifers makes interpolation between data points difficult. Secondly, the physical properties of the aquifers are often scale dependent, so that the value of a parameter at one scale may not be appropriate for use at a larger or smaller scale. Thirdly, there are problems of data quality and quantity which are particularly significant for these smaller aquifers. The quality of the pumping tests is variable and many results are from short duration pumping tests which are designed more to assess the yields of boreholes than to examine the properties of the aquifer. Also, data can be very irregularly distributed, being a product mainly of the evolving requirements of groundwater users and not of well-planned resource assessments. This irregular spacing can be both vertical as well as lateral, as in the case of thick structurally complex sequences with only scattered productive horizons.

Awareness of these inherent hydrogeological factors dictated the project's approach, which was to collect both data and knowledge about the aquifers. This permits the report to describe not only the magnitudes and variability of the aquifer parameters at a given tested locality, but also to provide some insight into factors controlling the properties, so that the results can be more confidently extrapolated. Project resources were therefore initially employed in data collection. This involved a detailed search through Agency records, with additional information from BGS, published and unpublished literature. Most of the data obtained were from analysed pumping tests, the results of which were entered in a database. The latter originally housed data on the major aquifers, collected under a preceding project, but the database needed to be significantly altered and expanded so as to manage efficiently the much larger number of aquifers involved. It was also linked with the BGS Core Analysis Database. The result comprises the National Aquifer Properties Database which is now a major UK geoscience resource, with data from more than 8000 pumping test analyses at over 8250 sites.

The second main strand of the project was the collection and summarising of knowledge about the aquifers. In addition to the collection of reports of hydrogeological studies and a literature survey, expert opinion was canvassed. The latter is a vital source of information that is not often published.

The results of these two approaches are synthesised in this report. After the introductory sections each chapter takes the form of a detailed review of the physical properties of a group of minor aquifers, subdivided as appropriate on stratigraphic or geographical grounds. The chapters are arranged in order of increasing age. The purpose of the review is to present the magnitudes and variability of the data (mainly from the database, but with other examples) in the context of current understanding of the aquifer systems involved and the controls on the data. To that end the review includes geological, geographical and physical hydrogeological aspects of the aquifers. Useful summaries of data from the database are included on the accompanying CD-ROM.

The intention of the report is therefore to acquaint the reader with the aquifer properties data values that characterise the aquifers in the context of what is known about the complexities of their hydraulic structure and the physical controls on the data. The reader is specifically dissuaded from taking raw values out of context. A further purpose of the report is provide a comprehensive set of references by which the reader can obtain more detailed information about particular areas of interest in an aquifer.

As a result of the collection and review of information about the physical properties of the minor aquifers in England and Wales, it is apparent that there are many areas in which knowledge is inadequate. For example, a critical comparison of the equivalent aquifer systems in the London and Hampshire basins was not possible in other than the most general terms. Similarly, the lateral variability in aquifer properties in the Lower Cretaceous aquifers of the Weald is suspected to arise partly from fault-controlled compartmentalisation, but the role of the faults is not well enough understood for predictive purposes. For all the effort expended on geological characterisation over almost two centuries of detailed study of English Jurassic rocks, the flow systems of the numerous arenaceous and carbonate minor aquifers of that system are in general poorly characterised. Very localised borehole development and the effects of tapping complex multi-aquifer sequences mean that the fracture-dominant, structurally-affected systems of older rocks of Palaeozoic age are in many cases barely conceptualised. Such gaps in our knowledge are inevitable considering the paucity of data. Nevertheless, the project has provided the first opportunity to review comprehensively the aquifer properties of this second rank of British aquifers whose role is so important in providing local sources of water supply for both private and public use.

KEY WORDS

UK aquifers, minor aquifers, Neogene aquifers, Palaeogene aquifers, Cretaceous aquifers, Jurassic aquifers, Permian aquifers, Triassic aquifers, Carboniferous aquifers, Devonian aquifers, Lower Palaeozoic aquifers, igneous aquifers, hydraulic conductivity, transmissivity, porosity, storage coefficient, specific capacity, yield.

1 Introduction

1.1 PROJECT DESCRIPTION AND SCOPE OF THE REPORT

1.1.1 Introduction

This project documents the aquifer properties of formations comprising minor aquifers in England and Wales, excluding drift aquifers. It follows a similar project which concentrated on the six major aquifer systems of England and Wales (Allen et al., 1997). It has comprised a three-year study, which commenced in 1996, and this report with accompanying CD-ROM is the principal product. The study was funded by the British Geological Survey (BGS) and the Environment Agency (EA), and was undertaken principally by BGS staff, with input from Agency staff. This is the first time that such a comprehensive document on the minor aquifers of England and Wales has been produced. While it can be used as a stand-alone reference, it also serves as a complement to the equivalent report on the major aquifers cited above.

For the Agency the production of this report forms part of a continuing commitment to the protection of the groundwater resources of the United Kingdom. Milestones in such protection were achieved first with the publication of the policy itself (NRA, 1992 and EA, 1998 second edition) and subsequently with the development of methodological tools to enable implementation of this non-statutory national policy. The latter have included the creation of source protection zones around public water supply abstractions and other wells providing water for potable or similar sensitive purposes. Over 2200 groundwater sources had been zoned by 1999, using a range of different techniques including internationally accepted computer-modelling packages. All require the input of aquifer parameters, often in complex hydrogeological situations. It is hoped that this report will encourage a consistency in approach to the development of models and underpin the long-term objective of producing defensible protection zones around groundwater sources that are respected by all.

For the BGS this report forms an important product of its basic scientific survey work. The collection, collation, interpretation and dissemination of hydrogeological information for public use are important parts of the Survey's role and both the present aquifer properties project and its predecessor falling entirely within that remit.

The specific objective of this report is to provide a source of information on the magnitude and variability of basic physical hydraulic parameters for the minor aquifers of England and Wales, excluding drift. A report on the many drift aquifers would comprise the final part of a comprehensive national compilation of aquifer properties.

One major difference from the latter report is that any work on British minor aquifers has to work on a broader canvas. There is not only a much larger number of formations involved but also the range of geological ages dealt with is much wider than the Mesozoic/Upper Palaeozoic age-span of the six rock systems comprising our major aquifer systems. This has hydrogeological significance in terms of degree of induration, dominant flow type, structural complexity and depositional extent. In the event, the data collection phase of the project revealed aquifer properties information at almost 1600 localities on 166 different water-bearing rock units in 31 aquifer groupings, numbers significantly in excess of what was anticipated at the start of the project.

The minor aquifers of England and Wales are widely used by public water undertakings but even more so by private abstractors to meet their supply needs. It is hoped that this report will be used as the major reference work on the current state of knowledge and known data availability for the physical properties of this important national groundwater resource.

1.1.2 Parameters and aquifers covered by the report

The aquifer properties addressed by the report are:

Permeability (as hydraulic conductivity)
Porosity
Transmissivity
Storage (as storage coefficient)

These parameters (which are defined Boxes 1 and 2 in Chapter 2) were chosen because they represent in a hydrogeological sense the fundamental physical properties of an aquifer, and are, in general, time invariant (although it is recognised that a term such transmissivity depends on the saturated thickness of the aquifer, which can vary with time). In addition, specific capacity (yield per unit drawdown) values are included for many of the formations described. Although as a derived calculation reflecting variations in the above-named parameters (principally transmissivity and storage) specific capacity is not strictly an aquifer property, it is nonetheless widely used as an indicator of productivity as an approximation for transmissivity. For many minor aquifers, there may be few or no values of transmissivity available from properly conducted and analysed pumping tests, not least because the tests are frequently carried out on wells destined for small-scale production where the costs of observation boreholes may not be justifiable. In such data-poor aquifers specific capacity values can facilitate comparisons and be helpful descriptors. In some cases where even specific capacities are sparse, yields have been cited, although it must be recognised that such data severely limit interpretation, being as much dependent on pump capacity and operator requirements as on the physical capacity of the aquifer drawn upon.

The report does not cover physical aspects of aquifers such as water levels, hydraulic gradients, hydraulic boundaries or recharge except to comment on their importance to the basic aquifer properties.

The principal aquifer aggregations for which data have been identified and collected are shown in Table 1.1 and comprise 31 groupings. As the minor aquifer part of the National Aquifer Properties Database contains 166 aquifer names, each formation or grouping may include several named aquifers. Most of the aquifer groupings listed in Table 1.1 have been referred to in this report, the principal criterion for inclusion being the availability of information on the aquifers concerned.

Table 1.1 Minor aquifer groupings in England and Wales.

Report chapter	Aquifer grouping	*No. of aquifer names
3 Neogene and Quaternary minor aquifers of East Anglia: the Crag	Crag	7
4 Palaeogene minor aquifers of the London and Hampshire basins	Eocene aquifers	7
	Lower London tertiaries	5
	Tertiaries	3
5 Cretaceous minor aquifers	Upper Greensand	1
	Lower Cretaceous/uppermost Jurassic sands/sandstones	11
6 Jurassic minor aquifers	Jurassic–Area 1	5
	Jurassic–Area 2	10
	Jurassic–Area 3	5
	Jurassic–Area 4	9
7 Permian and Triassic minor aquifers	Mercia Mudstone Group	5
	Aylesbeare Mudstone Group	4
8 Carboniferous minor aquifers	Upper Coal Measures	11
	Middle Coal Measures	1
	Lower Coal Measures	1
	Coal Measures	4
	Culm	5
	Millstone Grit	12
	Upper Carboniferous	3
	Dinantian Carboniferous Limestone	7
9 Devonian minor aquifers	Devonian/Carboniferous	1
	Upper Devonian	11
	Middle/Upper Devonian	1
	Middle Devonian	12
	Lower Devonian	14
	Devonian (undifferentiated)	7
10 Pre-Devonian and igneous minor aquifers	Silurian	3
	Ordovician	1
	Igneous	3
	Metamorphic	2

* Note: aquifer names are database entries from original test records; name overlap occurs in some cases.

The choice of these aquifers was primarily based on their classification as minor aquifers by the Agency. A small number of additional formations have been included where Agency abstraction licensing records have shown them to be locally significant for private supplies.

1.2 PROJECT APPROACH

Given the objectives of the project report[1] (to provide information on the magnitude and variability of aquifer properties) it was important to consider the extent to which parameter values might be ascribed to particular areas of aquifer — in other words, how prescriptive the document could be. For the aquifer properties there are three factors to be considered; aquifer complexity, available data quality/quantity and issues of scale.

1.2.1 Aquifer complexity

Aquifers in England and Wales do not in general approximate to the ideal aquifers on which most groundwater analysis is based. They are hydraulically complex, heterogeneous bodies of rock, often without clearly defined boundaries in which the magnitudes and variability of aquifer properties are imperfectly known.

The Neogene and Palaeogene aquifers described in this report are principally of the intergranular flow type where most water drawn from wells or springs has flowed to the source through the matrix. While structurally they may be relatively simple, with gentle dips and only modest faulting, the typically estuarine or shallow marine environment of deposition during most of the Cainozoic resulted in rapid facies variations which particularly affect the productivity of the sandy horizons, both down-dip and along the strike. Hydrogeological complexity arises from sedimentological factors such as the lateral impersistence of the beds, vertical and horizontal changes in texture and grain size, and variations in the admixture of fines. Thickness variations can arise not only from different rates of deposition but also from local penecontemporaneous periods of uplift and erosion. The numerous thin aquifer horizons of the London and Hampshire basins provide good examples of the complex hydraulic systems that can occur, with leaky aquifer and patchy aquifer conditions not uncommon.

The rather older water-bearing formations of the Mesozoic are also entirely sedimentary and tend to be more consolidated. However, the degree of consolidation and associated cementation can still be quite variable even with the same depositional group, as occurs for instance in the

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[1] The objectives of this project were substantially the same as those of its predecessor which compiled major aquifers physical properties data

Lower Cretaceous of the Weald where the Tunbridge Wells Formation contains both friable sandstones and massive indurated horizons such as the Ardingly Sandstone. Block-faulting can also introduce structural complexities. Compartmentalisation of aquifer blocks can result, and the very complex outcrop and subcrop pattern of the various Lower Cretaceous Wealden aquifers again provides a good example. The development of fractures in the more indurated formations provides the added complexity of dual porosity, and aquifers where intergranular flow dominates become uncommon in rocks older than the Cretaceous. Carbonate rocks are rather more common in the Mesozoic than in younger formations, and this has provided opportunities for solution enhancement of fractures, as in the case of the Middle Jurassic limestones from Dorset to north Yorkshire.

The Palaeozoic minor aquifers described in this report have all undergone long periods of burial and are without exception highly consolidated or recrystallised. Flow through fractures dominates in practically all formations older than the Triassic, with a commensurate decline in matrix porosity. Secondary features such as solution enhancement of joints in highly cemented and recrystallised limestone horizons also occur, with the development of karst features and conduit flow at outcrop and within the rock mass. Long periods of cyclic sedimentary deposition may result in aquifers being present only as relatively thin beds in an otherwise low permeability succession. In these circumstances productivity is less controlled by parent lithology than by structural effects such as folding, which may stimulate fracture development, or faulting which may link disparate parts of a predominantly low permeability succession. The cyclothems of the thick Coal Measures and Barren Measures successions scattered in sedimentary basins throughout England and Wales are good examples.

Structural deformation of Palaeozoic and older formations can be severe, ranging from folding and flexuring with associated joint development, through extensive normal, reverse and wrench faulting, to the development of cleavage. While such structural deformation generally increases the ability of these ancient formations to store and transmit water, the hydraulic effects are complex, such that deterministic groundwater flow modelling has only limited predictive value in terms of catchment definition. Igneous activity has also had its effects, with igneous rocks either themselves providing water-bearing horizons, as in the case of the weathered mantle of the Devon and Cornwall granites, or the opposite, where thin impermeable intruded dykes and sills act as barriers to vertical or lateral flow. Low productivity in many Lower Palaeozoic rock formations has tended to encourage utilisation of the upper 30 m or so where weathering effects are strongest. In addition, many boreholes in Wales are known or suspected to draw water from more than one aquifer, tapping shallow glacial deposits of Quaternary age as well as the parent bedrock.

As the foregoing indicates, the hydraulic complexity of Cainozoic aquifers in England and Wales is largely controlled by local sedimentary conditions of deposition while that of pre-Cainozoic aquifers in England and Wales is, to a large extent, determined by the degree to which they are fractured. For almost all aquifers in most areas of the United Kingdom knowledge of fracture location, fracture geometry, and the hydraulic behaviour of the fractures, is very poor. Where fractures are interconnected, fracture aperture is the fundamental control on rock permeability. In general, the more fractured the aquifer the less predictable are its hydraulic properties, and those aquifers in which flow occurs through fewer, larger fractures tend to have the least predictable properties.

Figure 1.1 illustrates this concept for various British minor aquifers. Thus the Crag and sands of the Bagshot Formation are considered to have minor fracturing and essentially intergranular flow, whereas the mid-Devonian limestones of south Devon are characterised by flow in conduits produced by solution, with virtually no matrix permeability. The increasing importance of fracture flow with age of formation applies as much to arenaceous aquifers as to carbonates.

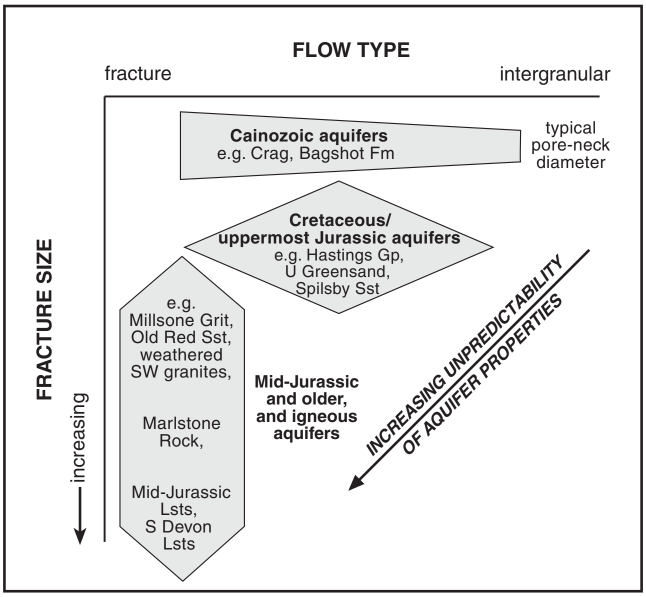

Figure 1.1 Flow types in British minor aquifers.

1.2.2 Data quantity and quality

Despite the inherent variability of the aquifers, as a result both of lithological complexity and of fracturing, it might be supposed that if sufficient data were available, distributed throughout the aquifers, then interpolations could be made between data points to provide parameter value estimates at any location. In practice the complexity of the aquifers is such that data requirements to achieve this result would be very large, and far in excess of the present data availability. The quantity and quality of data collected during the project are discussed in more detail in Chapter 2, but during the data collection stage it rapidly became clear that while there may be some information on many aquifers, none possess a comprehensive data set. The available physical properties data for the minor aquifers are generally too sparse, or too poor in quality to allow simple interpolations between data points to be made.

The problem of bias towards sites with higher yields is also rather more important with these aquifers than it was with the major aquifers. As British aquifers tend to be extensively developed, by implication those formations referred to as minor aquifers are classed as such by virtue of some limitation in the size or productivity of the groundwater resource. Thus dry or low-yielding wells which did not merit testing are more commonly encountered than in the major aquifers, although their existence would go unrecorded.

1.2.3 Scale problem

As a result of the significant heterogeneity of aquifers in England and Wales, measurements of a parameter obtained at one scale may not necessarily be appropriate for use at a different scale. For instance, transmissivity calculated from hydraulic conductivity values obtained in the laboratory on cores may be significantly different from those found from pumping tests. The commonest reason is that pumping test analyses represent the transmissivity not only of the matrix but also of any active fracture systems, while transmissivity cumulated from hydraulic conductivity measurements can only be the sum of matrix values. In turn pumping test values may be different from those appropriate for regional models (depending for example on the degree of regional interconnection of fractures). This can arise for instance in sandstone aquifers where test results from well-established production wells may appear to show higher transmissivities than flow-net calculations can justify, the difference being ascribed to localised development of the fracture system in the vicinity of the well-site due to prolonged pumping at production rates.

Thus the scale at which the data were obtained should be taken into account when considering their use. Furthermore, while a single averaged value of hydraulic conductivity may be appropriate for resources modelling, the significant vertical heterogeneity of most aquifers in England and Wales may render this simplification inappropriate for transport modelling, where actual flow paths need to be considered.

1.2.4 Scope of report and accompanying CD-ROM

In view of the foregoing factors no attempt has been made to produce a prescriptive document which provides an estimate of a physical properties parameter for every point in an aquifer. Instead, the philosophy of the project has been to obtain both data from, and knowledge about, each aquifer, and also to assess the limits of understanding of the aquifer properties.

This report therefore consists of a synthesis of knowledge about the magnitude, variability and controls on the properties of the minor aquifers of England and Wales. It contains information gleaned from tests on aquifer material at varying scales, from published and unpublished literature and from expert opinion (the latter becoming very significant in regions where data are few). Data are provided in the text, in diagrams and on the accompanying compact disk, but they are presented with the injunction that they be used with an awareness of the uncertainty arising from heterogeneity, scaling effects and lithological, structural and other controls present in the aquifers. Users of the project report may then derive the most appropriate values of parameters (as far as they are known) for their purpose, with an understanding of their context, and therefore of their likely validity.

1.3 READERSHIP

The report is designed to be used by hydrogeologists, who will have the skills necessary to understand the validity of the data when set in the appropriate hydrogeological context, or by those familiar with standard hydrogeological concepts and techniques. Thus the reader is assumed to be familiar with standard pumping test procedures and analysis (although not with core analysis techniques for which a brief discussion is provided in Box 3 of Chapter 2). Given this readership, the report assumes little prior knowledge of the aquifer properties of the aquifers covered. Thus it is likely to be useful both as a source of data for hydrogeologists already familiar with an aquifer and as an introductory guide for those working in a new area.

Users of the report will probably include those involved in groundwater protection zone work, water resource studies, and other physical hydrogeological investigations requiring knowledge of aquifer properties.

1.4 STRUCTURE AND USE OF THE REPORT

1.4.1 Introduction

The report and its accompanying compact disk are designed to be used in several ways; as a source of data, as a source of interpretative information placing the data in context, and as a guide to more detailed material. The report and its associated data may be considered as a hierarchy with the following form:

i The report text and associated diagrams provide a detailed discussion of the magnitudes, variation and controls on the aquifer properties of the minor aquifers, and in some cases notes on productivity and yields.
ii Underpinning the text are the summary pumping test and core analysis data results, provided as listings in a browser on the compact disk; this has an easy-to-use menu and is georeferenced to geological base maps to aid visualisation.
iii The listings provided on the compact disk are a summary of the much larger volume of information held on the National Aquifer Properties Database. This database is held by the BGS Hydrogeological Enquiry Service (to which application should be made for access to information[2]).

In general terms therefore it is intended that the user of this report should obtain information at a scale and level of detail appropriate for their purpose.

1.4.1 Report structure

Chapter 2 addresses aspects of data collection, storage and manipulation that were common to all the aquifers. Those interested in modelling considerations arising from the use of the information compiled in this report and associated database are referred to the chapter on this topic in Allen et al (1997).

From Chapter 3 onwards, the report is designed to allow the user to focus easily on particular aquifer systems. Given the large number of aquifer names (166, see Table 1.2), these have been aggregated into 31 groupings (see Table 1.1). These systems are arranged in eight chapters that descend the geological column from Neogene to pre-Devonian, with a section on igneous minor aquifers included in the pre-Devonian chapter. Chapters 3 to 10 comprise the main body of the report, in which the physical properties of the individual aquifers are reviewed.

Within each chapter there is a hierarchical structure, beginning with a general discussion. A geological overview with stratigraphic correlation table(s) has been included as

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a standard feature. This is in part in recognition of the very large number of aquifer names involved and in part because significant stratigraphical reclassification in recent years has given rise to renaming and reordering which could be perplexing to users more familiar with older interpretations. A review of the aquifer properties follows, in a form appropriate to the material being treated in each chapter. Thus the Crag chapter concentrates on one geographical area while the Palaeogene chapter deals separately with the material in the London and the Hampshire basins, providing links where possible. Other chapters like the Cretaceous and Jurassic deal with numerous aquifers that are locally important but of rather limited geographical extent. These have usually been handled by region to preserve the sense of aquifer *systems* rather than taking a particular formation with various local names and comparing it nationally 'down-dip and along the strike'. The older aquifer systems of the Carboniferous and Devonian are also treated regionally but for a different reason, having been separated by structural events into geographically distinct basins or depositional provinces.

Table 1.2 is a reference table listing all the aquifer names for which one or more aquifer property has been entered on the National Aquifer Properties Database. Boxes 1 and 2 in Chapter 2 give definitions of the parameters addressed by the report, with common ranges of values. The compact disk included with this manual provides data summaries on a locality basis of:

i Transmissivity and storage coefficient derived from pumping test results.
ii Specific capacity, either from pumping test analyses or from production well yield-tests.
iii Hydraulic conductivity and porosity derived from laboratory analyses of core material.

Almost 1600 localities have entries. The method of selection of representative values is described in Boxes 4 and 5 of Chapter 2. A browser is included which enables the user not only to inspect the data geographically, against a geological outcrop map of the area of interest but also to produce data listings whose layout is described in Boxes 6 and 7 of Chapter 2. Box 3 of Chapter 2 includes a description of the techniques used to obtain the hydraulic conductivity and porosity data. It is stressed that all data should be used only in joint reference with the information provided in Chapter 2 and the appropriate explanatory chapters, where the data may be set in context.

1.4.2 Report use

In broad terms the aquifer properties are presented in the report in a form which does not pre-suppose any particular use. Two main uses of the information in the report are envisaged however, requiring aquifer properties information to be employed in somewhat different ways.

Groundwater resources

In general terms the bulk properties of an aquifer are required in order to estimate groundwater resources. The main aquifer properties of interest are the aquifer's storage coefficient and its transmissivity (though factors such as recharge and hydraulic boundaries that are not covered by the report would also have to be assessed in order to evaluate resources). The report considers these factors in the light of current data, and opinion. Where appropriate the effect of the measurement methodology on the data values is assessed, also the likely controls on the parameter values (for example the effect of layering in the Mercia Mudstone or the significance of sandstone members in thick, otherwise low-permeability sequences in the Coal Measures).

Unlike the Chalk, the Permo-Triassic sandstones, the Lower Greensand and other major aquifers, regional resource models of the minor aquifers of England and Wales are very scarce. It is hoped that the data collated in this study will help stimulate efforts to model more minor aquifers. Of special concern are:

i Where abstraction is locally significant enough to cause potential competition for the groundwater resource between use categories/licensees.
ii Where local effects can have environmental significance (e.g. low flow effects in rivers or wetland derogation).
iii Where the resource may have a potentially significant new function, for example for aquifer storage and recovery.

Groundwater transport

The report may be similarly useful to those studying groundwater transport. However it is recognised that the study of the movement of pollutants in groundwater is significantly more complex than that of predicting borehole behaviour or estimating resources. Generally, in resource investigations it is not necessary to know the flow paths of groundwater, except in broad terms. However, fundamental to understanding groundwater pollutant movement, or to defining source protection zones is a knowledge of flow paths.

The complex hydraulic nature of many British aquifers, caused principally by fracturing, layering or both, makes the prediction of subsurface pollutant transport a challenge. This report may help users recognise these complexities and so promote realistic modelling of pollutant transport and source protection zones.

1.5 REPORT CURRENCY

This report was written using information collected from October 1996 to October 1998, although the database includes data originally collected earlier, as part of the preceding project on major aquifer properties (1993–1996). Like all database products, in order that the report and its accompanying compact disk may maintain its relevance as a source of information, they should be updated every few years.

1.6 REFERENCES

ALLEN, D J, BREWERTON, L J, COLEBY, L M, GIBBS, B R, LEWIS, M A, MACDONALD, A M, WAGSTAFF, S J and WILLIAMS, A T. 1997. The physical properties of major aquifers in England and Wales. *British Geological Survey Technical Report,* WD/97/34; *Environment Agency R&D Publication,* 8.

ENVIRONMENT AGENCY, 1998. *Policy and practice for the protection of groundwater* (2^{nd} edition). Environment Agency, Bristol

NATIONAL RIVERS AUTHORITY, 1992. *Policy and practice for the protection of groundwater.* National Rivers Authority, Bristol

Table 1.2 Reference table of aquifer/formation/unit names for which entries exist in the Aquifer Properties Database.

Report chapter	Aquifer grouping	Aquifer/formation/unit name
3	Crag	Clay and Crag
		Coralline Crag
		Crag
		Crag and Sand
		Norwich Crag
		Pleistocene Crag
		Red Crag
4	Eocene aquifers	Bagshot Beds
		Barton Clays
		Barton Sand
		Bracklesham and Bagshot Beds
		Bracklesham and Whitecliff Sands
		Bracklesham Beds
		Headon Beds
	Lower London tertiaries	Oldhaven Beds
		Reading Beds
		Thanet Beds
		Thanet Sands
		Woolwich and Reading Beds
	Tertiaries	Tertiaries
		Tertiary sand and gravel
		Tertiary sands
5	Upper Greensand	Upper Greensand
	Lower Cretaceous/ uppermost Jurassic Sands/Sandstones	Ashdown Beds
		Ashdown Sands
		Hastings Beds
		Leziate Beds
		Roach
		Sandringham Sands
		Spilsby Sandstone
		Tunbridge Wells Sand
		Upper Ashdown Sands
		Wadhurst Clay
		Weald Clay
6	Jurassic — Area 1	Lower Lias (Redcar Mudstone)
		Middle Lias
		Middle Lias (Staithes Formation)
		Ravenscar Group (Cloughton Formation)
		Ravenscar Group (Scalby Formation)
	Jurassic — Area 2	Blisworth Limestone/Great Oolite Limestone
		Corallian
		Elsham Sandstone
		Frodingham Ironstones
		Great Oolite (Cornbrash)
		Great Oolite and Forest Marble
		Lias — Marlstone Rock
		Lower and Middle Lias
		Lower Lias
		Portland
	Jurassic — Area 3	Corallian
		Forest Marble
		Lower Lias
		Upper Lias
		Upper Lias Sands (Midford/ Cotteswold Sands)
6 cont,	Jurassic — Area 4	Corallian
		Great Oolite (Forest Marble)
		Inferior Oolite
		Lower Lias
		Middle Lias
		Middle Lias (Downcliff Sands)
		Middle Lias (Pennard Sands)
		Portland Group (Portland and Purbeck)
		Upper Lias Sands (Bridport/ Yeovil Sands)
7	Mercia Mudstone Group	Arden Sandstone
		Keuper Marl
		Marl and Sandstone Skerries
		Mercia Mudstone
		Upper Keuper Marl
	Aylesbeare Mudstone Group	Aylesbeare Mudstone
		Clyst St. Lawrence Formation
		Exmouth Mudstone and Sandstone
		Littleham Marl
8	Upper Coal Measures	Barren Coal Measures
		Coalport Beds
		Coventry Sandstone Formation
		Enville Conglomerate
		Enville Group
		Etruria Marls
		Halesowen Group
		Keele Beds
		Keele Group
		Upper Coal Measures
		Upper Pennant
	Middle Coal Measures	Middle Coal Measures
	Lower Coal Measures	Lower Coal Measures
	Coal Measures	Coal Measures
		Middle and Lower Coal Measures
		Rotherham Sandstone
		Westphalian
	Culm	Bude Formation (Upper Carboniferous)
		Bude Formation
		Carboniferous Culm Measures
		Crackington Formation
		Culm Measures
	Millstone Grit	Ashover Grit
		Carboniferous Grit
		Chatsworth Grit
		Huddersfield White Rock
		Kinderscout Grit
		Millstone Grit
		Namurian
		Namurian Shales
		Pendle Grit
		Revidge Grit
		Roaches Grit
		Rough Rock
	Upper Carboniferous	Upper Carboniferous
		Upper Carboniferous shale
		Upper Carboniferous sandstone
	Carboniferous Limestone (Dinantian)	Buckator Formation (Lower Carboniferous)
		Carboniferous Limestone
		Chepstow Block

Table 1.2 continued.

Report chapter	Aquifer grouping	Aquifer/formation/unit name
8 cont.	Carboniferous Limestone (Dinantian) continued	Fell Sandstone Group Great Scar Limestone Lower Carboniferous Limestone Westleigh Limestone
9	Devonian/Carboniferous Upper Devonian	Pilton Shales Kentisbury Slates Morte Slates Old Red Sandstone Marl Pickwell Down Beds Polzeath Slate (Upper Devonian) Tavy Formation Torpoint Formation Upper Devonian Upper Devonian Limestone Upper Devonian slates Woolgarden slates
	Middle/Upper Devonian	Middle/Upper Devonian sandstone
	Middle Devonian	Devonian Gramscathos Beds East Ogwell Limestone Hangman Grits Middle Devonian Middle Devonian limestone Middle Devonian slate Mylor (Killas) Mylor Series Mylor Slates Plymouth Limestone Saltash Formation Trevose Slate (Middle Devonian)
	Lower Devonian	Bovisand Formation Dartmouth Slates Devonian Grampound Grit Devonian Staddon Grit Dittonian Old Red Sandstone Lower Devonian Lower Devonian Meadfoot Lower Devonian slates Lower Old Red Sandstone Meadfoot Group Old Red Sandstone Porthscatho Series Raglan Marl Staddon Grits
	Devonian (Undifferentiated)	Devonian Devonian grit Devonian shales Devonian slate Devonian slates and grits Devonian slates and sandstone Killas Brown Shale
10	Silurian	Ludlow Shales Silurian Wenlock Shales
	Ordovician	Llavnirn/Arneg
	Igneous	Dolerite Granite Pillow lava
	Metamorphic	Hornblende schist Lizard series

2 Information collection and use

2.1 TYPES OF INFORMATION COLLECTED

2.1.1 Introduction

A significant proportion of project resources were spent on obtaining information and upgrading the National Aquifer Properties Database to accommodate the much larger number of aquifers involved. As well as collecting a range of basic data — mainly pumping test results and some core analysis measurements — a review of knowledge from the literature was undertaken together with consultation of expert opinion local to the aquifer being reviewed.

The aquifer properties data were digitised and stored in the expanded National Aquifer Properties Database to enable them to be easily sorted and retrieved. A synthesis of this information was used with information obtained from the literature and from expert opinion to provide the source material for the aquifer review which comprises the following chapters of this report.

2.1.2 Core analysis data

Core analyses can provide point estimates of permeability, bulk porosity, and pore-size distribution within an aquifer. As the size of core samples is relatively small, laboratory results provide information on the aquifer properties at the matrix scale. The results of core analysis studies may be used, in combination with the results of field tests, to assess the relative contribution of matrix and fractures to the overall hydraulic response of an aquifer. Definitions are given in Box 1.

Most of the core data used in the report originate from the BGS Core Analysis Database. Over the last 30 years staff from the Aquifer Properties Laboratory of the BGS have performed core analysis studies on material from many British aquifers. A relational database has been established which contains information concerning the location, depth and stratigraphy of the samples, and includes the results of porosity, bulk density and permeability tests from over 13 000 samples from the aquifers of England and Wales. The samples were mainly obtained from cored boreholes, although there are a limited number of samples from surface exposures. A small quantity of core analysis data used for this report has been obtained from published and unpublished studies, including PhD projects. These data are generally in the form of averages, with little detail concerning the test procedure. This information, though referred to in the text, is not held on the database.

2.1.3 Pumping test data

Much pumping test information was obtained during the project and it is considered important because it is the only direct source of transmissivity and storage coefficient estimates for the aquifers on a local scale. Definitions are contained in Box 2.

Pumping test information was obtained mainly from the regional offices of the Environment Agency. Project staff visited all appropriate regional and area offices and recorded the results of pumping test analyses. At the outset the numbers of records of tests were unknown, but were believed to be perhaps several hundred. In the event, data were obtained from a total of almost 2100 tests at 1750 sites. The amount of data to be collected from each test needed to strike a balance between obtaining sufficient information to be useful in understanding the test result, but not so much as to exhaust project resources. No tests were re-analysed, as this was outside the project brief, but additional information such as type of test, duration etc. were collected.

A data collection form, or data sheet, was devised which would allow the salient features of the test (and the pumped borehole) to be recorded. Early in the project this was replaced by an electronic version, to allow the data to be entered directly by the BGS team member into a Microsoft Access™ field database on a lap top at the Environment Agency office. Both systems enabled data presented in many differing formats to be collected in one standard manner. In addition to recording aquifer and borehole details, test configuration and the results of test analyses, the data sheet allowed for an assessment of the quality of the test results. This is a subjective judgement made by the data collector and is based on an overall impression of how well the test was carried out and analysed. In addition, the nature of the test analysis (pumped well or observation well, constant rate or step test) was noted in order to identify preferred test and locality values (see later). Each data sheet was given a unique number, and the source of the data (e.g. pumping test report) was recorded in a separate data collection diary.

The data collected had many different origins. The most common by far arose from the statutory requirement to apply for a licence to abstract groundwater. Prior to 1963, no formal permission was needed to take water out of the ground; after this time the Water Resources Act of 1963 required all new abstractions to be licensed (the act was not retrospective). One purpose of this act was to be able to monitor, and thus regulate, the amount of water abstracted by any one supply with particular regard to the management of the resource and the effect of abstraction on other supplies.

In order to be able to assess the effect of abstraction for licensing purposes, data had to be made available for the assessors to make their decisions. For this purpose, it is as important to know the magnitude of local aquifer parameters, such as transmissivity and storage coefficient, as the yield of a borehole. It was in order to provide this information that pumping tests were performed on a more routine basis; indeed the latest revision of the Act in 1991 gives statutory powers to make a pumping test compulsory on any licence application to the Agency at their discretion.

While certain geographical areas were exempted (much of Wales for example remains licence-exempt) as were small amounts of abstraction defined as being for domestic use, larger amounts (non-domestic) were subject to licensing. This included such diverse applications as water supplies to farms, factories, breweries, quarries and many other sorts of industry. Latterly the large growth in the leisure industry has resulted in applications becoming common for large hotels, holiday complexes and golf courses. For the Crag in East Anglia, licence applications for irrigation well-point systems also provided some information. Above all,

BOX 1 DEFINITIONS OF AQUIFER PROPERTIES TYPICALLY DETERMINED IN THE LABORATORY

1 Permeability and hydraulic conductivity

1.1 *Definitions*

The term permeability, used in a general sense, refers to the capacity of a rock to transmit water. The *intrinsic permeability*, k [L^2], is independent of fluid properties. Units include m^2 and the darcy. The *hydraulic conductivity*, K [L/T] of a material is defined by Darcy's Law which can be stated as;

$$Q = KiA \qquad (B.1)$$

where Q = flow rate through the material
K = hydraulic conductivity (in the direction of flow)
i = hydraulic gradient (in the direction of flow)
A = cross-sectional area of the material

If the dimensions of Q are L^3/T and those of A are L^2 then hydraulic conductivity has the dimensions of L/T. Values are commonly quoted in m/d for aquifer materials. Hydraulic conductivity is related to intrinsic permeability by;

$$K = k\rho g/\mu \qquad (B.2)$$

where ρ = density of the liquid
g = acceleration due to gravity
μ = dynamic viscosity of the liquid

The hydraulic conductivity of a material is most accurately measured using a laboratory liquid permeameter. This measures the flow of formation liquid (water in the case of an aquifer) through a sample with accurately known dimensions caused by the imposition of a known head gradient. More commonly the conductivity of the sample to gas is measured and the result is converted to hydraulic conductivity.

1.2 *Values of hydraulic conductivity for different materials*

Material	**Hydraulic conductivity (m/d)**	**Source of data**
Unfractured Igneous rocks	$<10^{-5}$	Freeze and Cherry (1979)
Shale	10^{-8}–10^{-4}	Freeze and Cherry (1979)
Chalk (matrix)	10^{-6}–10^{-2}	Allen et al. (1997)
Sandstone	10^{-5}–10^{-1}	Freeze and Cherry (1979)
Sherwood Sst (matrix)	10^{-5}–10	Allen et al. (1997)
Clean sand	10^{-1}–10^{3}	Freeze and Cherry (1979)
Gravel	1–10^{3}	Freeze and Cherry 1979)

2 Porosity

Porosity ϕ [dimensionless] is commonly defined as the ratio of the pore volume to the bulk volume of a material. Several types of porosity may be defined within this general definition.

2.1 *Total porosity*

If a volume of rock V contains a total volume of pore space $V\rho_T$ (where $V\rho_T$ includes both matrix and fracture porosity) then the *total porosity* ϕ_T is defined as:

$$\phi_T = (Vp_T/V) \times 100 \text{ per cent}$$

Total porosity is measured by some logging techniques (e.g. neutron logs) with corrections for clay-bound water applied where appropriate. The parameter is not normally measured by hydrogeological core analysis, but values could be obtained by using the liquid resaturation technique (see below) on a sample both before and after desegregation.

2.2 *Total interconnected porosity*

Some of the pore space in a rock may be isolated from the main pore network and cannot participate in groundwater flow processes. If the remaining total volume of interconnected pores is Vp_I then the *total interconnected porosity* ϕ_I may be defined as;

$$\phi_I = (Vp_I/V) \times 100 \text{ per cent} \qquad (B.4)$$

Total interconnected porosity can be accurately measured by standard core analysis techniques. These include liquid resaturation (involving the measurement of weight increase of an initially dry sample after careful resaturation with a liquid under laboratory conditions), and helium porosimetery (in which helium gas is expanded into the accessible pore space and the pressure drop noted). Borehole resistivity logs also measure total interconnected porosity. The difference between total porosity and total interconnected porosity is not thought to be large for British aquifers.

2.3 *Values of porosity for different materials*

The porosity of a rock can only lie in the range 0% to 100%. Typical values of total interconnected porosity are given below.

Material	**Porosity (%)**	**Source of data**
Shales	0–10	Freeze and Cherry (1979)
Limestones	0–20	Freeze and Cherry (1979)
Sandstones	5–30	Freeze and Cherry (1979)
Sherwood Sandstone	2–35	Allen et al. (1997)
Chalk (UK)	3–55	Bloomfield et al. (1996)

2.4 *Drainable porosity*

The part of the total interconnected porosity which will drain under gravity is sometimes referred to as *drainable porosity*. The term *effective porosity* is also sometimes used in the same sense. However effective porosity may also be used to mean kinematic porosity and therefore its use can be ambiguous.

2.5 *Kinematic porosity*

Only a proportion of the total interconnected porosity will be involved in fluid flow. This is normally termed the *kinematic (or dynamic) porosity*, ϕ_k (although as mentioned above, effective porosity is also sometimes used). The relationship between the kinematic porosity and total interconnected porosity is likely to be complex, and may depend both on aquifer structure and flow characteristics. The measurement of kinematic porosity will depend on its precise definition; laboratory experiments may be one way of investigating the parameter; tracer tests are another.

BOX 2 DEFINITIONS OF AQUIFER PROPERTIES TYPICALLY DETERMINED BY PUMPING TESTS

1 Transmissivity

Transmissivity T [L^2/T] can be defined as the product of hydraulic conductivity and aquifer thickness, with values usually quoted as m^2/d. Transmissivity is only well defined for two-dimensional horizontal flow. Transmissivity is generally measured by tests in the field. For example a pumping test on a fully penetrating borehole may be used to determine the transmissivity of an aquifer, or a packer test may yield the transmissivity of a section of aquifer. These values of transmissivity may then be used to provide estimates of average hydraulic conductivity for the section of aquifer tested.

2 Storage

2.1 Specific storage

The *specific storage* S_s [L^{-1}] of a saturated aquifer is defined as the volume of water that a unit volume of aquifer releases from storage under a unit decline in hydraulic head. Two mechanisms are involved; the compaction of the aquifer caused by increasing effective stress, and water expansion caused by decreasing pressure.

Specific storage may therefore be expressed as:

$$S_s = \rho_w g(\alpha+\phi\beta) \qquad \text{(B.5)}$$

where ρ_w = water density
g = acceleration due to gravity
α = aquifer compressibility
β = water compressibility
ϕ = porosity (ϕ_I)

2.2 Storage coefficient

The *Storage coefficient* S [dimensionless] is the volume of water which an aquifer releases or takes into storage per unit surface area of aquifer per unit change in head. Its use is sometimes restricted to confined aquifers, or is sometimes additionally used to encompass unconfined aquifer storage.

2.3 Specific yield

Specific yield S_y [dimensionless] has been used in two different ways; to represent drainable storage only, or as the total storage term for unconfined aquifers (that is, drainable plus elastic storage).

Aquifer storage terms are commonly evaluated by pumping test analysis, although other methods are sometimes used, for example water balances, or laboratory estimates.

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applications for groundwater abstraction for public supply provided many good pumping tests.

The standard of pumping test data from licence applications varied greatly. Tests ranged from a few hours with data being collected from only the abstraction well, to tests of several days (usually five or seven) with one or more observation wells. This criterion was a factor in the awarding of a suitable test quality rating. In general it is true to say that the more recent the test and the larger the amount of water abstracted, the higher the quality of the test. This is a direct reflection of the realisation of the importance of this knowledge and the ability to carry out a successful test.

Whilst licence applications were the source of most of the data, especially historically, the growth of hydrogeology as a specialist scientific subject led to other data sources becoming available. For the major aquifer programme which preceded this project, much of the more recent and usually better quality data were available in reports of scientifically based studies. The former River Boards, River Authorities and other similar public bodies carried out much hydrogeological research for their own purposes. Most of the pre-National Rivers Authority/Environment Agency bodies did research into many topics. Artificial recharge schemes, river regulation schemes, river augmentation schemes, basin studies and many other forms of work necessitated pumping tests to provide information. This has been less the case with the minor aquifers, partly due to the more limited size of water resource that a particular minor aquifer could offer and partly because these formations are more often tapped by numerous small private abstractions than by large public water supplies.

Since the privatisation of the water industry in 1989 and the establishment of the National Rivers Authority and its successor the Environment Agency as regulatory body, the potential for acquiring pumping test data has increased. The Agency carries out a limited amount of its own research (albeit sometimes via contractors) while the water companies also conduct operational development projects and other forms of data gathering of their own volition. The water companies need to know the amount and extent of their water resources to be able to supply their customers. They have an obligation to supply the Agency with details of tests if they wish to obtain a licence for abstraction, although research work including test pumping may be carried out and the results kept confidential by the company concerned.

The final sources of data were minor and similar to those tapped for the preceding major aquifers programme, that is published proceedings from meetings and symposia, MSc and PhD theses deposited with the Environment Agency, engineering reports on roads and tunnels, inputs to computer model studies, plus many other, often small, studies from which aquifer parameters were gathered.

In addition to data obtained from the Agency, pumping test analyses were obtained from BGS records, from literature (published and unpublished) and to a lesser extent from industry. Most relevant water company data was obtained from Environment Agency records, as a result of licence applications. Problems of data confidentiality precluded direct access to data from consultants.

For certain data-poor aquifers, specific capacities and yields were collected to supplement more directly applicable aquifer properties data (see Section 2.2.2.2). These came from Agency licensed abstraction registers, from the BGS National Well Record Archive and from BGS geological sheet memoirs.

2.1.4 Model calibration data

Unlike the major aquifers, where a number of regional groundwater resource models exist, published modelling exercises for the minor aquifers are sparse, and so aquifer properties data used in model calibration have not generally been a source of information for this report.

2.1.5 Literature sources

Where available, information concerning the magnitude of, variation in, and particularly the controls on, aquifer properties, was obtained from literature, a substantial review of which was carried out. This included published literature, unpublished reports held by the Environment Agency and BGS, and theses held by Universities. Not surprisingly, the body of literature for the minor aquifers of England and Wales is much slimmer than that for the major aquifers. Much guidance on the source of relevant literature was obtained from Agency hydrogeologists and colleagues in the BGS.

Information collected included geophysical logging, geological, hydrogeological, hydrological and hydrochemical information pertinent to the physical properties of the aquifers.

2.1.6 Expert opinion

This was a very important component of the study. Much of the aquifer properties information is held in the form of unpublished views or routine work undertaken by acknowledged authorities on aquifers in different areas, and accumulated as a result of much practical experience on the abstraction and management of the groundwater resources these aquifers represent. As far as possible these have been consulted — in particular the Agency regional hydrogeologists — and their opinions incorporated into the report.

2.2 PROJECT DATABASE

2.2.1 Introduction

The aquifer properties database in Microsoft Access™ originally devised for the major aquifers programme needed to be significantly altered to handle the increased stratigraphic complexity posed by the minor aquifers project. The resultant database redesign, associated geological investigation and data reclassification involved significant extra effort. This complexity took a number of forms:

i There are many aquifers involved: the data collected cited 166 aquifer names, which even after aggregation through creation of a summary table represented 31 general formation groups.

iii There are water-bearing formations described in this report which range in age from Neogene to Precambrian, the stratigraphical complexity of which is immense: the inclusion of information which included stratigraphic descriptors now superseded by later interpretations gave rise to much nomenclatural confusion.

iii There were several hundred data entries with valid test results whose field geology descriptions either assigned a lithology (e.g. red sandstone) instead of a stratigraphic horizon, or were excessively general (e.g. Jurassic limestone) or were too ambiguous to assign without further investigation (e.g. Upper Carboniferous sandstone). These sites comprised too large and valuable a dataset to be discounted and about 200 were successfully reclassified through a GIS exercise so that they could be properly utilised.

iv Unlike the previous programme, which dealt with many aquifer property values for a few aquifers, the new information collected has comprised fewer values for many more aquifers. In order to provide some quantitative background to those aquifers where transmissivities and storage coefficients were sparse, a specific capacity field was added. Some aquifers were so data-poor that only yields could be used to indicate the productive capacity of the formation, and a selection of these became a subject for special effort (see Section 2.2.3.2).

During the life of the project pumping test data were collected, digitised and stored along with core analysis data from the BGS core analysis database. The upgraded PC-based database has proved flexible enough to handle a wide range of the queries required during data manipulation.

The relational database structure was developed to hold the pumping test and core analysis information, illustrated as 14 interlinked tables in the entity relationship diagram in Figure 2.1. All information contained in the database is connected by means of a site identifier, which is allocated to each site from which information has been obtained (usually a borehole or core analysis site). The database tables hold information such as site locality and geology, borehole geometry, aquifer name and grouping, pumping test analysis types and results, core sample location and core analysis results.

The structure of the database enables queries to be readily designed to extract information using a variety of criteria, such as location, aquifer name or general aquifer grouping, geology, type of test or type of analysis. A conservative philosophy has been adopted for data entry, in that data in different tables are only connected if there are clear reasons for doing so. Therefore, for example, a new set of data is allocated a new site number unless it clearly comes from an existing site.

All valid test values have been employed in the tabular and graphical summaries used in the following chapters in order to provide the most comprehensive dataset for statistical calculations. However, for the more general user, it was recognised that further screening would be helpful to provide indications of geographical distribution of parameters across an aquifer. Sites have therefore been aggregated in order to provide representative aquifer property values for a locality, which comprises either a single site, or a grouping of two or more sites located within 100 m of each other. Locality values and backdrop geological maps have been employed for the accompanying CD-ROM. This constitutes only part of the National Aquifer Properties Database, which in January 2000 contained data on 7837 sites, of which the minor aquifers comprised 1751 sites at 1593 localities.

The National Aquifer Properties Database now contains eight major information types, of which the data for the minor aquifers with associated core analysis results comprises two (Table 2.1).

2.2.2 Database contents — core analysis data

Table 2.2 summarises the total number of sites and number of samples tested from the aquifers covered by the project. Details of sample numbers as a function of geographical or stratigraphical distribution, and numbers of specific tests performed on samples for each aquifer are given in the appropriate chapters of the report.

Sometimes each sample taken from a core was tested for porosity and permeability, and in a few cases two samples were taken from a given depth in a borehole, to provide a horizontal and a vertical estimate of permeability. In general terms, the array of core data is much more limited than that which is available for the major aquifers. This is reflected not only in the much smaller number of sites but also in the very limited coverage of formations; many minor aquifers of some significance have no permeability or porosity measurements or at best only a (probably unrepresentative) handful of values.

A brief description of core analysis techniques is given in Box 3 as these are may not be familiar to the field hydrogeologist.

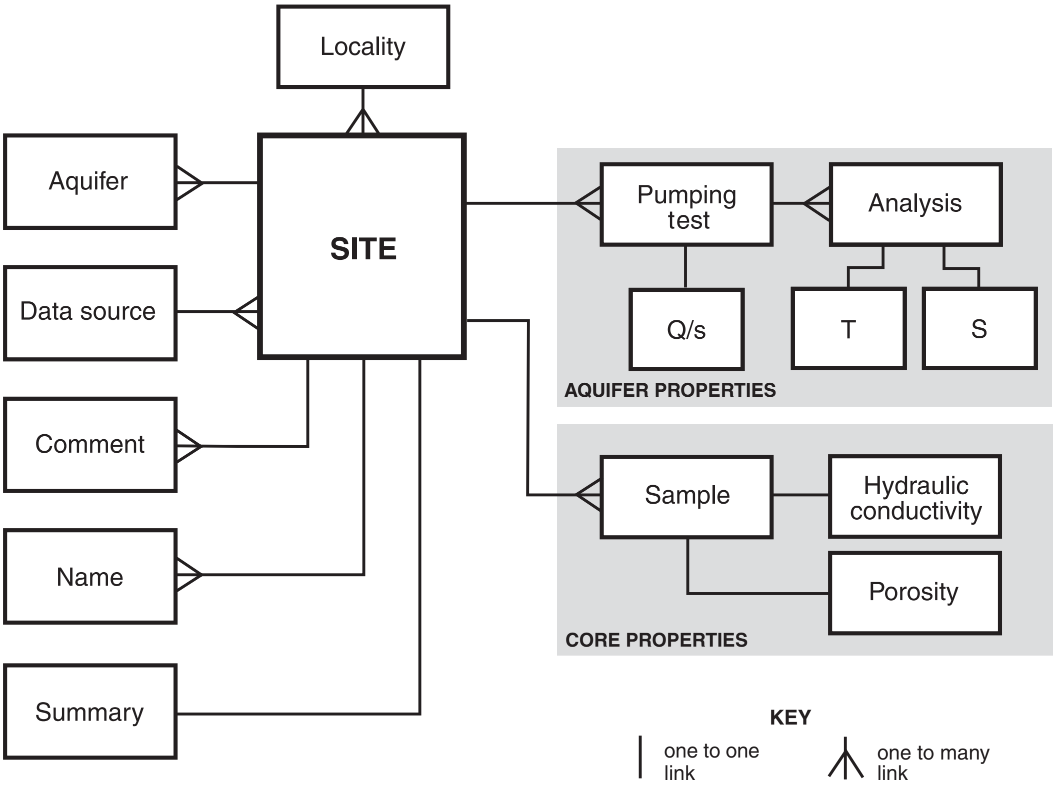

Figure 2.1 An entity relationship diagram for the National Aquifer Properties Database.

Table 2.1 Information groupings in National Aquifer Properties Database (January 2000).

Grouping code	Type of information	No. of sites in grouping	No. of pumping tests
1	Major aquifers, stratigraphically classified	4251	5146
2	Minor aquifers, stratigraphically classified	1751	2090
3	Quaternary aquifers, internally unclassified	487	470
4	Core data, partially classified	937	1
5	Data described by lithology only	47	39
6	Multiple aquifers	43	45
7	Aquifers of uncertain classification	62	76
8	Non-aquifers	2	2
9, 10	Other	254	211
	Totals	**7837**	**8080**

Table 2.2 Distribution of core analysis data held in the National Aquifer Properties Database.

Aquifer grouping	Number of sites	Number of samples
Minor aquifers	210	2367
Major Aquifers	727	12614
Totals	937	14981

2.2.3 Database contents — pumping test data

2.2.3.1 *Data distribution*

Pumping test data collected during the course of the project were mostly collected digitally directly on to an Access™ proforma. Although the database is not static and information is added as resources allow, in January 2000 the database held information from 2090 pumping tests at 1751 sites tapping minor aquifers, comprising 21% of the sites on the National Aquifer Properties Database at that time. Each borehole for which aquifer properties data are held in the database has been tested by pumping at least once, and that test has produced at least one transmissivity or specific capacity estimate, and possibly a value of storage coefficient. Some boreholes have been tested several times, and many tests have multiple results due to several different analyses having been carried out. Table 2.3 provides an overview of key statistics relative to the minor aquifers information grouping.

2.2.3.2 *Data quality*

As discussed in Section 2.1.3 a general assessment of the quality of pumping test data was made during data collection if there was sufficient raw test information to enable an assessment of quality to be made. Eight hundred and one tests, or a little under 40% of the total number of test results were eligible for a quality rating. Also, while a quantitative assessment of quality was used (on a scale of one [highest quality] to five [poor quality]) the fact that the data were collected by several different people meant that the assessment was inevitably subjective. Thus the ratings should be considered merely to distinguish good or very good data/results (ratings one and two) from poor or very poor data/results (ratings four and five), with an intermediate area of average data/results (rating three).

BOX 3 CORE ANALYSIS TECHNIQUES

1 Introduction

There are a variety of standard core analysis techniques that may be used in hydrogeological studies. These are commonly based on those used in the hydrocarbon core analysis industry (e.g. American Petroleum Institute, 1956). The principal techniques are:

(i) *Liquid resaturation* and *helium gas expansion* (HGE) tests to determine values of interconnected porosity and bulk density.

(ii) *Gas permeability* tests to obtain a value of permeability (in a form amenable to conversion to an intrinsic, or equivalent liquid, permeability, and/or conversion to a hydraulic conductivity).

(iii) *Mercury injection capillary* (MICP) tests to determine pore throat-size distributions.

Additionally, centrifuge tests may be used to obtain specific yields and capillary pressure characteristics, porous plate tests may be used to investigate capillary pressure characteristics, and electrical tests may be used to obtain resistivity indices and formation factors. The following is a brief description of the liquid resaturation porosimetry and gas permeability methods used to obtain the porosity and gas permeability data held in the core analysis database.

2 Core analysis measurement methods

Interconnected porosity, is measured using the liquid resaturation methods. Sample porosity is determined by liquid resaturation according to the Archimedes principal. For each sample measurements are made of: dry weight (w, g), saturated weight in air (S_1, g), saturated weight under saturant (S_2, g), and the density of the saturant (ρ_f, g/cm$^{3)}$. From these values dry bulk density (ρ_b, g/cm^3), grain density (ρ_g, g/cm^3), and interconnected porosity (ϕ_I, %) can be calculated as follows (after American Petroleum Institute, 1956):

$$\rho_b = (w\rho f) \,/\, (S_1 - S_2) \text{ g/cm}^3 \qquad \text{(B6)}$$

$$\rho_g = (w\rho f) \,/\, (w - S_2) \text{ g/cm}^3 \qquad \text{(B.7)}$$

$$\phi_I = (S_1 - w) \,/\, (S_1 - S_2) \times 100\ \% \qquad \text{(B.8)}$$

Errors associated with the liquid resaturation porosity measurements are approximately ± 0.5 porosity percent.

Permeability is measured using nitrogen. Gas permeability tests are performed on samples constrained in a core holder. A constant gas flow rate is established through the sample. Sample size (where A is cross-sectional area, mm^2, and L is length, mm), gas flow rate (Q, cm^3/sec), gas viscosity (μ, cP), gas injection pressure (P_g, abs. atm.), and atmospheric pressure (P_o, abs. atm.) are recorded and used to calculate a measured gas permeability, k_g as follows (after American Petroleum Institute, 1956):

$$k_g = 1.974 \times 10^{-11}\ \mu\ Q\ L\ P_o \,/\, \{\ A\ [\ (P_o + P_g)^2 - P_o^2\ ]\}\ \text{m}^2 \qquad \text{B.9)}$$

where 1 mD is equivalent to 9.87 × 10^{-16} m$^{2\cdot}$ Measurement errors are typically of the order of ± 2%. Gas permeability data in the core analysis database are rounded to one significant figure below 9.87 × 10^{-16} m^2 and are rounded to two significant figures above 9.87 × 10^{-16} m^2.

Gas permeabilities obtained by core analysis measurements may not be equivalent to the intrinsic, or liquid, matrix permeability of the aquifer material, as they may be effected by a molecular phenomenon known as ‘gas slippage’. Consequently, the following empirical correction has to be applied (Lovelock, 1977):

$$\log_{10} k = 1.1 \log_{10} k_g - \log_{10} 2.1 \qquad \text{(B.10)}$$

Field measurements of permeability are usually expressed as hydraulic conductivity, *K*. The following expression can be used to convert permeability into hydraulic conductivity:

$$K = k\ g\ \rho \,/\, \mu \qquad \text{(B.11)}$$

where k is permeability, g is gravitational acceleration, r is the density of water, and m is the dynamic viscosity of water. Therefore at 10°C

$$K\ \text{(m/day)} = 6.408 \times 10^{-4}\ k\ \text{(mD)} \qquad \text{(B.12)}$$

Table 2.3 Summary of data availability for the minor aquifers of England and Wales.

Statistic description	**Number of values**			
	Pumping test	**Preferred test***	**Site**	**Preferred locality**
Transmissivity values	2940	1132	954	862
Storage coefficient values	674	345	305	275
Specific capacity values	2090	1663	1438	1370
Test yield values	1794	1794	1565	N/A
Totals	**No. of tests 2090**	**N/A**	**No. of sites 1751**	**No. of localities 1593**

* See 2.3.1.2 for explanation of this term.

The results for the 801 tests are shown in Figure 2.2. Almost 1300 tests were not allocated a rating because insufficient raw data were seen. The others were approximately normally distributed over the quality range, with 159 tests meriting a high quality rating of one or two or about a fifth of the total. This figure may be an under-estimate because in general test results obtained from the literature are likely to be good, yet they would be un-rated because the raw data had not been seen. It should be borne in mind that even more than was the case with the major aquifers, the dataset is also likely to be biased towards sites with high transmissivities. Reasons for this bias include the fact that boreholes tend to be drilled where a reasonable yield is expected; also wells with low yields are less likely to be tested, and unproductive or dry exploratory wells are unrepresented.

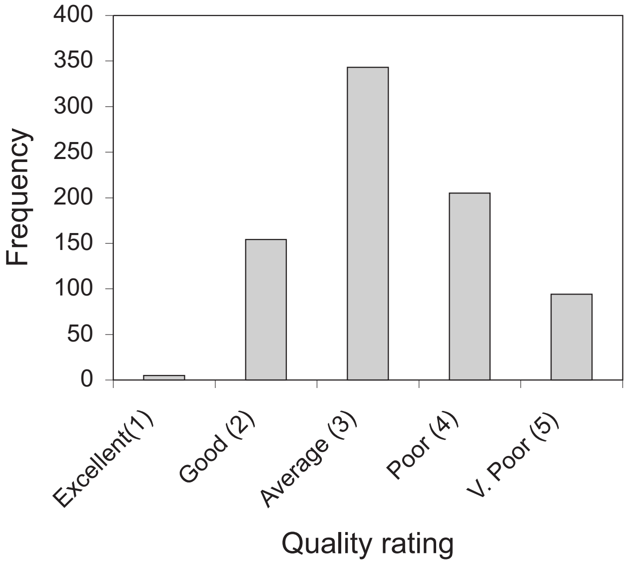

Figure 2.2 Distribution of quality ratings for pumping test data.

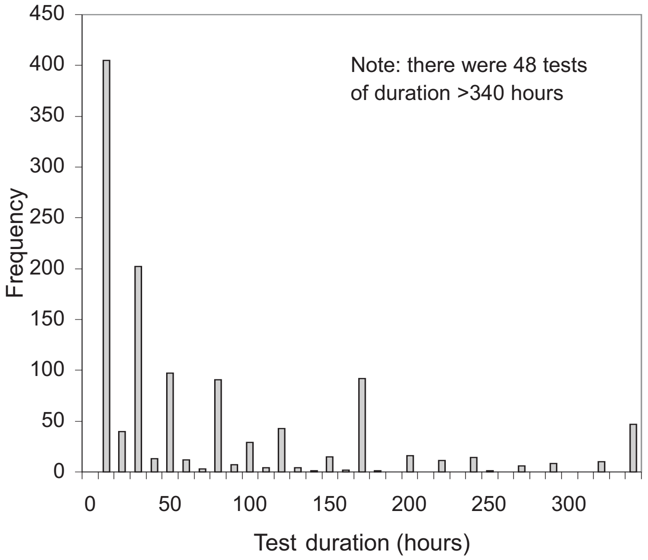

Figure 2.3 Distribution of test duration for pumping test data for tests of up to 14 days.

It should be pointed out however that tests with average or poor quality ratings were not necessarily poorly carried out. On the contrary, the test procedure may have been exemplary, but if the data analysis techniques did not match the data well then the test would be marked down. These problems of non-conformance to standard test analysis techniques were quite common. In many cases pumping tests were analysed by a variety of techniques, producing a range of analytical results, often with no preferred value (the handling of this information for the accompanying CD-ROM is discussed in Section 2.3.1.2).

Another measure of data quality might be the availability of analyses based on observation borehole results; the database holds such information for around 25% of the tests where this information is known (Table 2.4).

The database holds duration of test information for 1222 tests, just under 60% of the total. The distribution of test length for tests of up to 14 days is shown in Figure 2.3 (the database holds information for 48 tests of longer than 14 days). This information is not necessarily a measure of data quality, but rather of the volume of aquifer that the test sampled. However in practical terms longer tests provide more information for the analyst to assign appropriate aquifer properties parameter values. Figure 2.3 indicates that over 60% of tests with a recorded duration were undertaken for two days or less. These are more prone to analysis difficulties than longer tests.

While the database holds information on almost 2100 pumping tests at over 1750 sites, significantly more than had been anticipated at project inception, it is as well to point out that these cover 31 formation groupings representing 166 aquifer names in formations ranging in age from Neogene to Precambrian. Thus there are many instances where aquifer properties information for a particular minor aquifer is sparse. These data-poor aquifers may nonetheless be productive and support numerous abstractions, and for a selection (the Jurassic Marlstone Rock, the Triassic Aylesbeare Mudstone Group, and the Ordovician and Cambrian rocks of west Wales) an additional data gathering exercise was undertaken. The purpose was mainly to demonstrate that for many formations, the absence of formal pumping tests (and consequent opportunity for calculation of transmissivity and storage coefficient that these could present) does not signify that the strata are either impermeable or unproductive. That is, absence of aquifer properties values does not equate to aquitard or aquiclude status.

The additional data gathered from Agency abstraction licence records, from the BGS National Well Record Archive and in one case from a PhD thesis comprised either specific capacities or yields. As there were no calculated values with which to correlate, the specific capacities cannot be used to infer an empirically derived transmissivity. Similarly, yields are as much dependent on the type and capacity of the pump employed and the requirements of the borehole user as on the intrinsic properties of the formation tapped. Nevertheless, in the absence of calculated aquifer property values, such data do at least provide some indication of the water-bearing and water-yielding properties of a given formation.

Table 2.4 Source of analytical data for pumping tests in the minor aquifers.

Source of pumping test results	No. of tests	% tests where source type recorded
Observation well data	193	25
Pumping well data	571	75
Source type not recorded	526	—
Tests not providing a T or S value	957	—
Tests providing one or more T, S or Q/s value	2090	—

A conclusion from all three data-poor aquifer exercises, was that more use is made of the formations for water-supply than might have been expected. Consequently, this report is not likely to be exhaustive in its coverage of formations comprising minor aquifers in England and Wales, and it is quite likely that there are stratigraphical horizons not referred to that are locally productive enough to support limited abstraction. An obvious generic example would be one or more arenaceous or solution-enhanced fractured limestone horizons in an otherwise argillaceous or mudrock-dominant succession.

In general terms therefore, while data for a significant number of pumping tests are available for numerous minor aquifers the quality of the data is variable and care needs to be exercised in using the results.

2.2.4 Database contents — future directions

The future development of the database will take two directions; administration and content.

2.2.4.1 *Administration*

The database is currently (January 2000) held within Microsoft Access™. It is intended to merge the database with the BGS WellMaster hydrogeological database. This will allow better cross-reference of aquifer properties with other data sets, for instance with water quality. WellMaster is hosted within Oracle™ and will hold data on over 100 000 water wells/boreholes in England and Wales. WellMaster will in the future be accessible over the Internet.

2.2.1.1 *Potential future parameters*

Anisotropy

Anisotropy relates to scale. Although sedimentary rocks exhibit anisotropy on a small scale due to factors such as grain size variation or degree of cementation, permeability anisotropy mostly relates to larger scale heterogeneity with spatial correlation, almost exclusively due to bedding. This will normally give a vertical anisotropy which would vary with depth. Occasional low permeability horizons will have a dominant effect on the vertical permeability, averaged over some depth interval.

For fractured rocks anisotropy is observed both vertically and horizontally. However, it is not until a certain scale is reached that it may be appropriate to treat such systems as if they were a uniform ‘porous medium’, and only then is it sensible to refer to or quantify anisotropy. Horizontal anisotropy can be determined from long-term pumping tests with distant observation wells.

When a constant-rate pumping test in a horizontally anisotropic aquifer is analysed by a Jacob plot, the transmissivity value obtained will be the geometric mean of the principal components of transmissivity. The value of storage coefficient obtained will depend on the position of measurement of drawdown in relation to the principal directions of transmissivity and on the ratio of maximum and minimum transmissivity values.

Diffusivity

It is interesting to note that for most purposes, the storage parameters of an aquifer (storage coefficient and specific yield) are never used other than in combination with permeability parameters in the form of a hydraulic diffusivity, the obvious exception being in the estimation of aquifer storage. It therefore appears that diffusivity is, sometimes, a more fundamental parameter than the storage parameters.

Diffusion coefficient

Molecular diffusion is an important dispersive mechanism within the aquifer matrix for pollutants in intergranular and dual porosity aquifers. Diffusion coefficients are normally measured under carefully controlled laboratory conditions.

Dispersion

The term dispersion refers to the process of spreading during transportation: solutes, particles and heat are all dispersed in groundwater. The processes of matrix diffusion and adsorption both have dispersive effects, however the term hydrodynamic dispersion refers more specifically to spreading due to spatial variations in the flow velocity. These are caused by:

i Different velocities of molecules at different points along an individual pore or fracture channel due to the drag exerted on the fluid by the roughness of the pore/fracture surface.
ii Differences in the pore sizes/fracture apertures along the flow paths followed by the water molecules.
iii The tortuosity, branching and interdigitation of pore channels or complexity of fracture plane paths.

The process takes effect at many scales, from the pore-scale upwards.

Hydrodynamic dispersion presents two major problems: (a) there is no generally accepted physical and mathematical description for heterogeneous media, and (b) it is very difficult to perform experiments (e.g. tracer tests) to quantify the dispersive characteristics of rocks.

If advective transport could be fully characterised throughout the system, there would be no additional dispersion phenomenon to consider. So, strictly speaking, dispersion is not a process in its own right, it is rather an expression of the fine (often random) detail of the advection process. Dispersion must therefore be related to the advective model (conceptual or mathematical) in use, particularly to its scale of averaging.

2.3 USE OF INFORMATION COLLECTED DURING THE STUDY

2.3.1 Use of pumping test information

2.3.1.1 *General*

Although pumping tests often provide the only direct estimates of transmissivity and storage coefficient in aquifers there are inherent problems with their use.

The interpretation of pumping test data (for example drawdown versus time) may be ambiguous unless other, possibly circumstantial, information is taken into account. Objective analysis of pumping tests is not possible, and subjective elements in analysis include the choice of the model used to analyse the test (a particular problem in fractured British aquifers), type-curve fitting (when used), and the choice of data points for analysis. An additional difficulty encountered in the present study is that tests have often been analysed by several different methods without an indication by the analyst as to which analysis is considered to be the most appropriate.

Pumping test information collected by the project has been used in three main ways:

i Data from the National Aquifer Properties Database have been used to provide the information in the general user CD-ROM accompanying this report.
ii Data from the database have been used in the aquifer review chapters.
iii Aquifer properties information derived from reports and expert opinion has been incorporated in the aquifer review chapters.

2.3.1.2 *Nature of the pumping test data provided on the CD-ROM*

Details of the methodology used to produce the data shown in the CD-ROM are given in Boxes 4 and 5, but it is appropriate to consider the general approach here. The aim of the CD-ROM is to provide summary aquifer properties data for different localities for the general user, and therefore a methodology had to be developed which would enable an appropriate value to be distilled from the range of information which may be available at a given locality. It should be noted here that the term 'locality' as used in the report has a specific meaning, being defined as an area encompassing sites lying within 100 m of each other. The reasons for this are given below.

The problem posed is that the database may hold several estimates of transmissivity for a pumping test, and commonly there is no indication from the analyst as to which value is the most appropriate for the test. There may also have been several tests at a site, and finally there may be several sites clustered together at a locality (defined as encompassing all sites within 100 m of each other). The need is to obtain a representative value for a test and then to obtain a summary value for each locality. The methodology used to obtain locality values of transmissivity and storage coefficient therefore had to account for pumping test results held in the database which ranged from single values for a single test, to a number of results with no indication as to which if any was the most appropriate, from several tests performed at several sites in a given locality.

The solution adopted has been to use a simple set of criteria (in the form of database queries) to choose a value of transmissivity or storage coefficient considered to represent the most reliable analysis (or average of analyses) for a particular test. This is referred to as the preferred test value. Another set of criteria is then used to obtain a preferred locality value. These criteria were applied to all the pumping test data held in the database. The methodology had four advantages:

i There was a transparent, objective approach to selection of data.
ii The method could subsequently be readily revised if necessary.
iii By reducing the raw data to a summary locality value, problems of data confidentiality are avoided.
iv Data duplication is removed i.e. where two different site identifiers refer to the same borehole but there is insufficient information to make the decision to merge them.

The locality value could be simply the sole analysis for a single test at a single site, or the mean of numerous analyses from a number of tests performed at more than one site in a locality. The criteria were designed to select the highest quality test results, or those least affected by near-borehole effects, to characterise the locality. While there were 118 localities containing more than one site, in 91% of cases a given locality only comprised a single site. This situation is rather different to that in the major aquifers where multi-well localities are by no means uncommon. Of the multi-site localities about three-quarters contained only two sites, with 17 localities containing three or more sites.

The menu routines on the accompanying CD-ROM give the locality values of transmissivity, storage coefficient and specific capacity. Details of listing layout are given in Box 6.

2.3.1.3 *Use of locality data*

It should be stressed that since the locality preferred values made available on the CD-ROM are a synthesis of the various test results obtained at the locality, they should be used with care. The methodology employed prioritises high quality data and emphasises aquifer rather than near-borehole characteristics. However, in condensing a variety of data to a single locality value, detail is inevitably lost. Also the queries are relatively simple, and naturally cannot be expected to produce definitive values at complex sites where results cover a large range but where the analyst(s) favoured no particular value. Therefore while the preferred locality values provide a summary estimate for each locality, and may illustrate the areal variability of parameters across an aquifer (if observation well readings are involved), they do not give a full representation of any particular site.

Workers requiring details of pumping tests and results (for example types, duration, water levels, analysis methods) for particular sites should seek direct access to the National Aquifer Properties Database which is held by the BGS at Wallingford. In particular it is recommended that for modelling purposes the full database information be sought. As it is intended that the National Aquifer Properties Database be updated at intervals, use of data directly from the database also has the advantage that a more up-to-date dataset can be used than that presented in this report.

2.3.1.4 *Use of database pumping test data in aquifer review chapters*

The following chapters contain numerous statistical summary tables. The statistics chosen to describe the data are typically the total number of records, then for a given parameter, the maximum and minimum value, arithmetic and geometric mean, the median, interquartile range and the 25/75 percentiles.

Data are also described and related graphically in the form of histograms and cumulative frequency plots. Both are provided, as the cumulative frequency distribution provides the most statistical information, but the histogram conveys the general form of the data more easily. Since transmissivity, storage coefficient and specific capacity data tend to extend over several orders of magnitude they are plotted on a logarithmic scale.

Graphs and statistical descriptions are only provided where the data-set in question was populated with ten or more values. While there were many minor aquifer horizons for which meaningful statistics could not be produced due to insufficient data, it was nevertheless possible to produce many summaries for transmissivity, storage coefficient, specific capacity and in some cases for yield. Where applicable, and where ten or more corresponding values were available, scatter plots of transmissivity against specific

BOX 4 SELECTION OF AQUIFER PROPERTY PREFERRED TEST VALUES

Figure 1 shows the flow chart used to select test values of transmissivity. Where the database has only a single transmissivity estimate for a test then this was naturally taken. Where there are several values but where the analyst indicated one as being the most appropriate (the 'best value') then this was taken. Where no particular estimate is indicated as being the most appropriate then a simple set of rules was applied to obtain the test value. For constant rate tests observation borehole data were given priority, followed by abstraction borehole data. Multiple values from observation boreholes were averaged geometrically (since they may represent different areas of the aquifer) while multiple values from abstraction boreholes were averaged arithmetically (since they represent different estimates of transmissivity at the same site). If step test data only are available these were averaged.

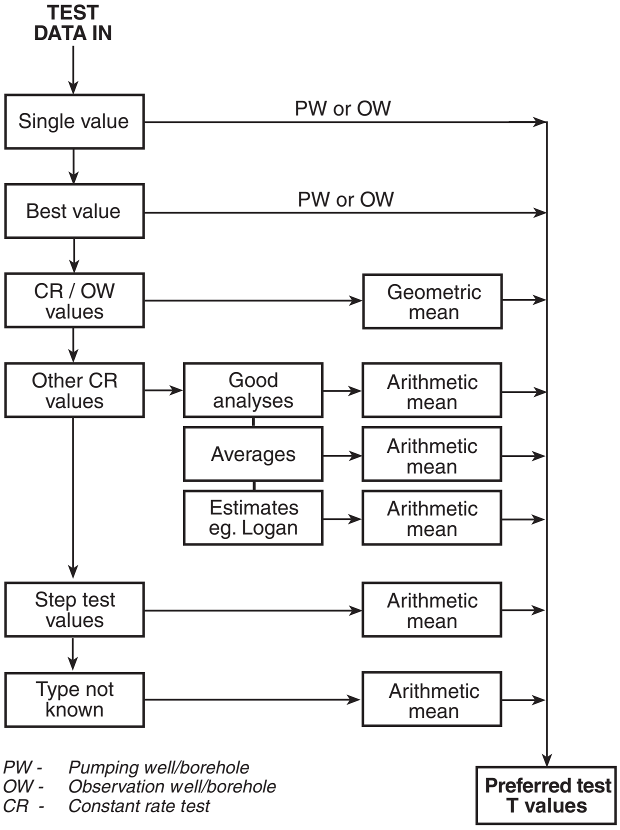

Figure 1 Flowchart of selection procedure for preferred test transmissivity values.

The selection of the value of specific capacity and storage coefficient for each test was made according to the flow charts shown in Figures 2 and 3 respectively. As with the transmissivity data, single values or best values were taken, where applicable, followed by an average of available data.

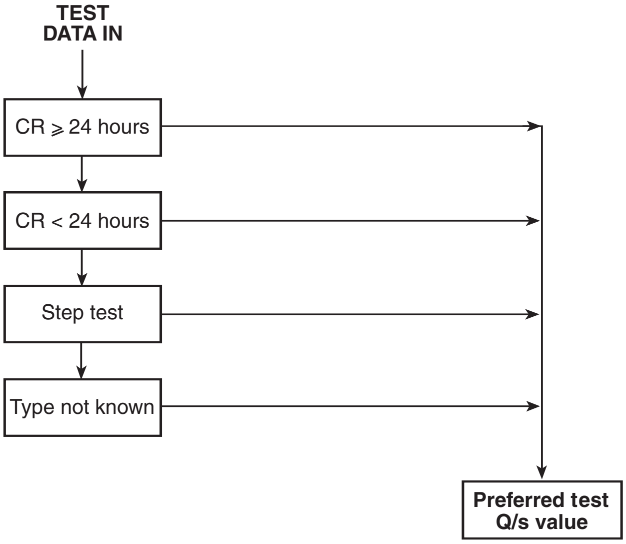

Figure 2 Flowchart of selection procedure for preferred test specific capacity values

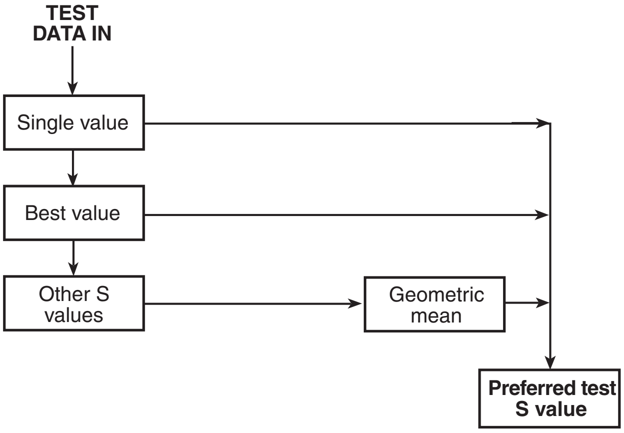

Figure 3 Flowchart of selection procedure for preferred test storage coefficient values

capacity have also been included. These enable the reader to assess whether, given a near steady-state specific capacity for a well without a valid pumping test analysis, an empirically-derived transmissivity may be assigned to a locality.

2.3.1.5 *Use of reported pumping test information*

In addition to the numerical results of test interpretations referred to above, much useful information about pumping test results, aquifer heterogeneity and borehole behaviour was obtained from published and unpublished literature and from expert opinion. This proved generally useful in the aquifer review chapters. Where there was a dearth of data, much reliance has necessarily been placed on the practical experience of hydrogeologists, but more generally this information has helped provide a framework of knowledge in which to set all the test results as well as the locality estimates of transmissivity, storage coefficient and specific capacity provided on the CD-ROM.

2.3.2 Use of core analysis information

2.3.2.1 *General*

Core analysis provides direct values of matrix permeability and interconnected porosity, but, more so than with the pumping test information, there are significant problems of

BOX 5 SELECTION OF AQUIFER PROPERTY PREFERRED LOCALITY VALUES

Where several pumping tests were carried out at a site, then a procedure was used to enable the better quality tests to be chosen to represent the site values. For a locality with more than one site tests were treated as if they had been carried out at one site, and the best tests were again identified, in order to characterise the locality. The scheme used to select a transmissivity and storage coefficient for a locality is illustrated in Figures 4, 5, and 6 respectively and summarised in the table below. Initially, constant rate tests with a high quality rating (one or two) were selected, and, if there were several of them, the test values were averaged. For tests with a lower quality rating, or without a rating, test results from observation borehole values were taken and averaged. Where no observation borehole data were available preference was given to tests longer than a day, followed by shorter tests. Then high quality step test values were used, followed by medium quality step test data. Test values from tests with no information were considered next, followed by data from tests considered to be poor.

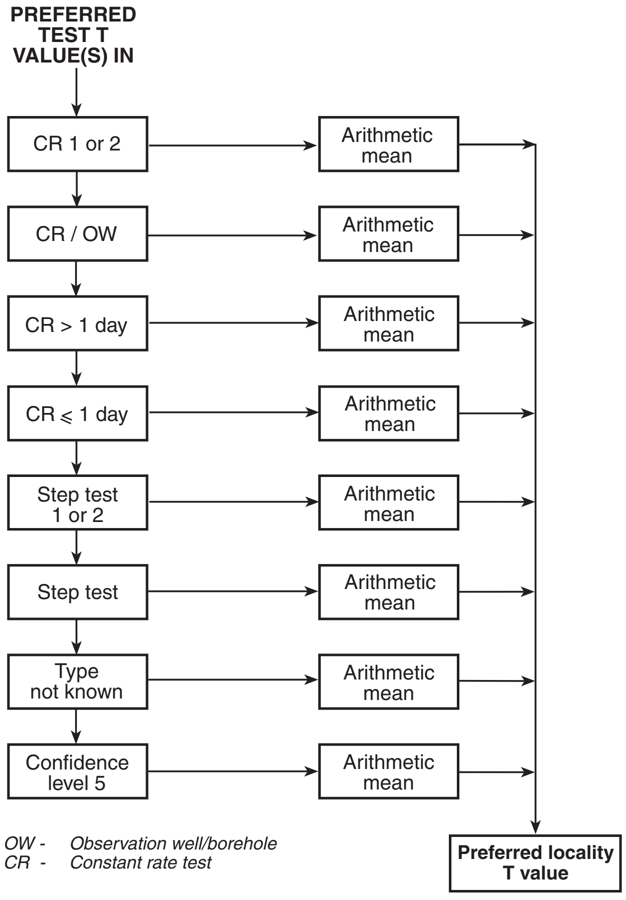

Figure 4 Flowchart of selection procedure for preferred locality transmissivity values.

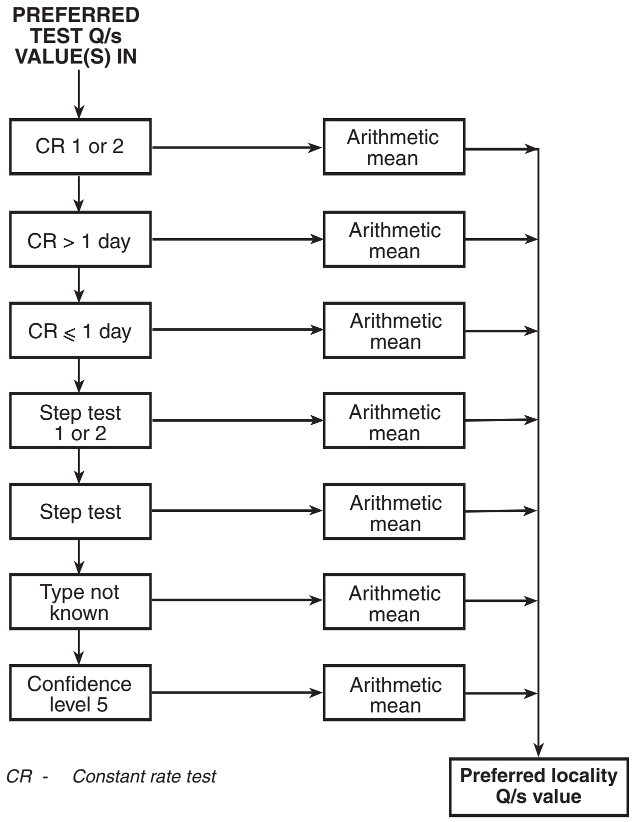

Figure 5 Flowchart of selection procedure for preferred locality specific capacity values.

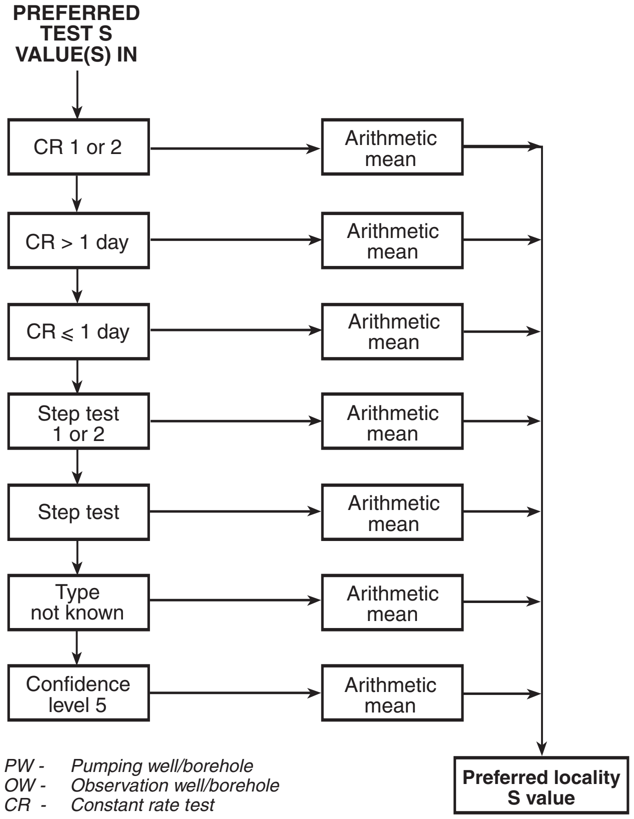

Figure 6 Flowchart of selection procedure for preferred locality storage coefficient values.

BOX 5 Continued.

Codes used to denote the origin of locality transmissivity and storage coefficient data

Origin	**Explanation**
CR 1 or 2	Arithmetic mean of test values from constant rate tests with a quality rating of one or two
CR OBH	Arithmetic mean of observation borehole test values from constant rate tests with a quality rating of three or four or without a rating
CR > 1 day	Arithmetic mean of test values from constant rate tests with a quality rating of three or four or without a rating where the test was longer than one day
CR = 1 day	Arithmetic mean of test values from constant rate tests with a quality rating of three or four or without a rating where the test lasted for one day or less
Step test 1 or 2	Arithmetic mean of test values from step tests with a quality rating of one or two
Step test	Arithmetic mean of test values from step tests with a quality rating of three or four or without a quality rating (in the case of S values the arithmetic mean of any step test data)
Type not known	Arithmetic mean of test values from tests where there is not sufficient test data to fit them into any of the above criteria
Confidence level 5	Arithmetic mean of test values from tests with a quality rating of five

BOX 6 LAYOUT OF THE LOCALITY AQUIFER PROPERTY LISTINGS ON THE CD-ROM

Data presentation

Locality data is provided as a series of menu options on the accompanying CD-ROM using the above scheme. Each value of transmissivity, specific capacity and storage coefficient is annotated by a description of the source of the data, that is, at what point on the flow charts the data were obtained (Figures 4, 5 or 6 or the table above). In general terms, the further down the flow chart the data were obtained, the less reliable are the values. Results have been rounded to two significant figures. The data on the CD-ROM has been grouped by aquifer, covered in a similar way to the report review chapters, in order of increasing age.

An explanation of the meanings of the column headings used in the listings is given below.

Locality	Locality numbers. The numbers take the form of a five digit integer and are prefixed by AQ to distinguish them from other numbering systems (locality numbers given in this report have no meaning outside the report).
Map	10 km map sheet identifiers (e.g. SP57).
Easting/Northing	Easting and northing of the locality using the full numeric grid coordinates (i.e. the first number denotes the relevant 100 km grid square).
Name	The locality name (where several boreholes at one locality are summarised this may be the name of one of the boreholes).
Aquifer	The aquifer unit tested (some tests test more than one aquifer unit, but these are not included in the data sets on the CD-ROM).
Min	The minimum value in the database for this locality; transmissivity in m^2/day, storage coefficient (dimensionless) or specific capacity (m^3/m/day).
Max	The maximum value in the database for this locality; transmissivity in m^2/day, storage coefficient (dimensionless) or specific capacity (m^3/m/day)
No_values	The number of individual values in the database for this locality.
Preferred	The preferred locality value; transmissivity in m^2/day, storage coefficient (dimensionless) or specific capacity (m^3/m/day)
Source	Information about the type of test or tests from which the locality value was derived (explanation is given in table in Box 4).
St_dev	Not used for transmissivity, storage coefficient and specific capacity summaries.
Aq_code	This is an internal code used to select data for display in the CD-ROM browser software, and relates to chapter headings within the printed manual. It will not normally be displayed.

data bias and adequacy. Core analysis results are biased towards lithologies which are sufficiently consolidated to be sampled. Thus unconsolidated or poorly consolidated sands which might have relatively high permeabilities may not be sampled, while low permeability materials, such as clays or shales, may be sampled but not not tested. These features are well illustrated in the Crag and Palaeogene aquifers where there is a distinct paucity of core data. In addition, insufficient samples may have been taken from a cored interval to characterise adequately the variations in matrix properties and it is pertinent to comment that no studies seem to have been carried out to date in British aquifers to identify statistically robust sampling regimes. It must therefore be concluded that, while available core data may be used as a guide to the range of values likely to be encountered within an aquifer, there are few sites with enough information to justify a direct comparison with data from larger scale field measurements.

2.3.2.2 *Nature of the core data provided on the CD-ROM*

Core analysis data from the database are included on the CD-ROM. Average matrix values are provided for each site for which data are held, with maxima and minima shown where there are ten or more values for a given parameter for that site. Average values are only intended as a guide, since at many sites only a few samples are available from the aquifer. Details of listing layout are given in Box 7.

2.3.2.3 *Use of core analysis information in aquifer review chapters*

Core analysis data from the database have been used to indicate matrix values of porosity and permeability in the aquifer review chapters. Generally the approach has been to show the distribution of data for a given named aquifer or aquifer subdivision in the area under discussion. There is provision for horizontal and vertical hydraulic conductivities to be recorded on the database, distinguishable by the suffix '-V' or '-H' to the sample number. The data are shown on similar types of plot to the pumping test data (see above), except that while hydraulic conductivities are shown on a logarithmic scale, porosities are given on a linear scale.

BOX 7 CORE DATA AVERAGING AND SELECTION OF LOCALITY VALUES ON THE CD-ROM

1 Porosity

Porosity within a given lithology tends to follow an approximately normal distribution and therefore porosity data are usually averaged by arithmetic mean. The same practice is adopted on the listings in the CD-ROM.

2 Permeability

Matrix permeability commonly ranges over two or more orders of magnitude. Consequently, estimation of a single-valued effective matrix permeability for an aquifer from core data is not a trivial problem. Theoretical studies suggest that effective matrix permeability must be greater than the harmonic mean and less than the arithmetic mean of core permeability measurements, and it can also be shown that there are a continuous range of possible permeability probability density functions (Jensen et al., 1987). A number of studies have investigated the form of permeability (or hydraulic conductivity) distributions for a variety of rock types (e.g. Bennion and Griffiths, 1966; Freeze, 1975; Lambert, 1981). These studies suggest that hydrocarbon reservoir rocks and aquifers often exhibit lognormal permeability distributions. In addition, indirect evidence, from the distribution of borehole specific capacities (Davis, 1969) and from Monte Carlo tests on random block porous media (Warren and Price, 1961), also indicates that permeability is lognormally distributed. The most appropriate single-valued best estimator for a lognormal distribution is the geometric mean, i.e. the n^{th} root of the product of n observations. Note that the geometric mean has a value that is less than the arithmetic mean but greater than the harmonic mean, and consequently lies within the theoretical bounds of Jensen et al. (1987). Although there is no rigorous justification for arbitrarily choosing either the arithmetic mean, geometric mean or the harmonic mean as an estimator to describe a given permeability frequency distribution, the geometric mean has been used in the listings to calculate average permeabilities from core data, on the basis that permeability distributions are commonly lognormally distributed.

3 Selection of hydraulic conductivity and porosity average values from core analysis data

Data are given for localities, which group one or more sites on 1:25 000 map sheets as in the case of pumping test sites. For the core information, however, data for each sampling site are listed, so there may be more than one line of data per locality. Permeabilities are given as hydraulic conductivity values in m/d. Averages of horizontal samples only are given. Porosities are given as per cent values.

An explanation of the meanings of the column headings used in the listings is given below.

Locality	Locality numbers. The numbers take the form of a 5 digit integer and are prefixed by AQ to distinguish them from other numbering systems (locality numbers given in this report have no meaning outside the report).
Map	10 km map sheet identifiers (e.g. SP57).
Easting/Northing	Easting and northing of the locality using the full numeric grid coordinates (i.e. the first number denotes the relevant 100 km grid square).
Name	This label is not used for hydraulic conductivity or porosity summaries
Aquifer	The aquifer unit tested
Min	The minimum value in the database for this locality; hydraulic conductivity in m/day, or porosity as %. Where there are fewer than ten samples in the database for a locality this value is not given.
Max	The maximum value in the database for this locality; hydraulic conductivity in m/day, or porosity as %. Where there are fewer than ten samples in the database for a locality this value is not given
No_values	The number of samples considered in the database for this locality. Not detailed where there are less than ten samples as a locality
Preferred	The preferred locality value at the location; geometric mean of hydraulic conductivity in m/day, or arithmetic mean of porosity as %
Source	This label is not used for hydraulic conductivity or porosity summaries.
St_dev	Standard deviation of porosity values as percent. Not used for hydraulic conductivity summaries.
Aq_code	This is an internal code used to select data for display in the CD-ROM browser software, and relates to chapter headings within the printed manual. It will not normally be displayed.

Reported core analysis information has been used along with the database data as the basis for the assessment of the matrix properties of the aquifers. The importance of the matrix information varied between aquifers and was treated accordingly. Given the general increase in consolidation, cementation and degree of fracturing with formation age, core data from aquifers older than the Mesozoic are both sparse and of limited value in assessing the true transmissivity of the formations from which the cores are drawn.

2.3.3 Use of other information

Many other sources of information have been used in the project to provide insight into the aquifer properties of the major aquifers (see Section 2.1.5). The discussion in the regional aquifer review chapters is mainly based on a combination of information from these sources and analysis of the data from the database.

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3 Neogene and Quaternary minor aquifers of East Anglia: the Crag

3.1 INTRODUCTION

The Neogene is part of the Cainozoic (formerly referred to as the Tertiary), the earlier part being represented by the Palaeogene. These two systems are subdivided into series as follows:

Neogene	Pliocene
	Miocene
Palaeogene	Oligocene
	Eocene
	Palaeocene

The Crag, part Neogene and part Quaternary, (see Table 3.1) is the only aquifer of Neogene age of any significance within England and Wales. Palaeogene aquifers are dealt with in the following chapter.

The Crag deposits of East Anglia include the Pliocene Coralline Crag, overlain by the Pleistocene Red Crag, Norwich Crag, and Wroxham Crag. Communally the formations were always known as 'the Crags' until Arthurton et al. (1994) formally introduced a Crag Group, although this was only intended to include the Red and Norwich crags. The term 'Crag Group' is also used in this sense in Moorlock et al., in press. However, the term 'the Crag' is used here as a general term to include all the deposits.

The Crags resemble each other to a large extent, and sometimes may only be distinguished by their fossil content (Price and Tuson, 1961); consequently they are usually not differentiated on drillers' logs. Their lithology is very variable, including gravels, shelly sands, sands, silts, laminar and lenticular clays. At depth, the beds contain reduced iron which results in a green staining. Nearer the surface, their oxidation gives rise to a yellow and brown colouration.

The deposits are utilised for groundwater in the east of the area, and become particularly important where the underlying Chalk contains saline water. As described below, there are particular problems with developing the deposits for groundwater resources.

3.1.1 General geology and stratigraphy

The Crag occurs across eastern East Anglia and Essex. Figure 3.1 shows the extent of the outcrop (of all the Crags apart from the Coralline Crag), and includes contours on its base. The top of the Crag declines quite evenly from about 90 m AOD in the south-west, to sea level at the coast in the east and north, a dip of about 1 m per km.

The base of the Crag rests unconformably on Palaeogene deposits (mostly clays) in the east and south, and elsewhere on the Upper Chalk. It is largely overlain by later Quaternary deposits, except where these have been removed by erosion. Those immediately overlying the Crag are as follows:

- Kesgrave Formation (pre-Anglian, fluvial) over the area south of a line between Aldeburgh, Bury-St-Edmunds and Bishops Stortford
- Ingham Formation (pre-Anglian, fluvial) along the valley of the River Waveney
- Corton Formation (Anglian, glacial) over the area north-east of a line between Lowestoft, Norwich and Cley-next-the-Sea (includes the Corton Sands and North Sea Drift)
- Lowestoft Formation (Anglian, glacial) over most of the rest of the area.

Of these the Kesgrave, Ingham and Corton formations are dominantly sands and gravels. The Lowestoft Formation is largely till but is commonly underlain by some sand and gravel.

The Crag represents the late Neogene and early Pleistocene infilling of the western margin of the North Sea Basin. Troughs on the sub-Crag surface are reflected in increased thickness of Crag (Price and Tuson, 1961). The deposits are largely marine, but coastal and estuarine deposits become increasing important upwards. The four formations which are now recognised are defined by virtue of their being separated by unconformities representing phases of westward transgression and eastward regression of the North Sea (Hamblin et al., 1997) (see Table 3.1).

As described earlier, the four formations known as 'the Crag' are the Coralline Crag, Red Crag, Norwich Crag and Wroxham Crag. While the first three names are widely known, the term Wroxham Crag Formation is relatively new; it post-dates the surveys of Saxmundham, Lowestoft and Great Yarmouth. There has never been much doubt about the position of the Coralline Crag–Red Crag boundary,

Table 3.1 Outline stratigraphy and relationships of the East Anglia Crags.

	EAST ANGLIAN STAGE	EAST ANGLIAN LITHOSTRATIGRAPHIC UNITS	
QUATERNARY	CROMERIAN	Bacton Member Mundesley Member West Runton Member	CROMER FOREST-BED FORMATION
	BEESTONIAN	Runton Member	
	PASTONIAN	Paston Member Sheringham Member	WROXHAM CRAG
	PRE-PASTONIAN	Sidestrand Member	
	BAVENTIAN	Westleton Beds Easton Bavents Clay	NORWICH CRAG
	BRAMERTONIAN	Chillesford Clay Member	
	ANTIAN	Chillesford Sand Member	
	THURNIAN	Thorpness Member	RED CRAG
NEOGENE	LUDHAMIAN		
	PRE-LUDHAMIAN	Sizewell Member	
		Aldeburgh Member Sudbourne Member Ramsholt Member	CORALLINE CRAG

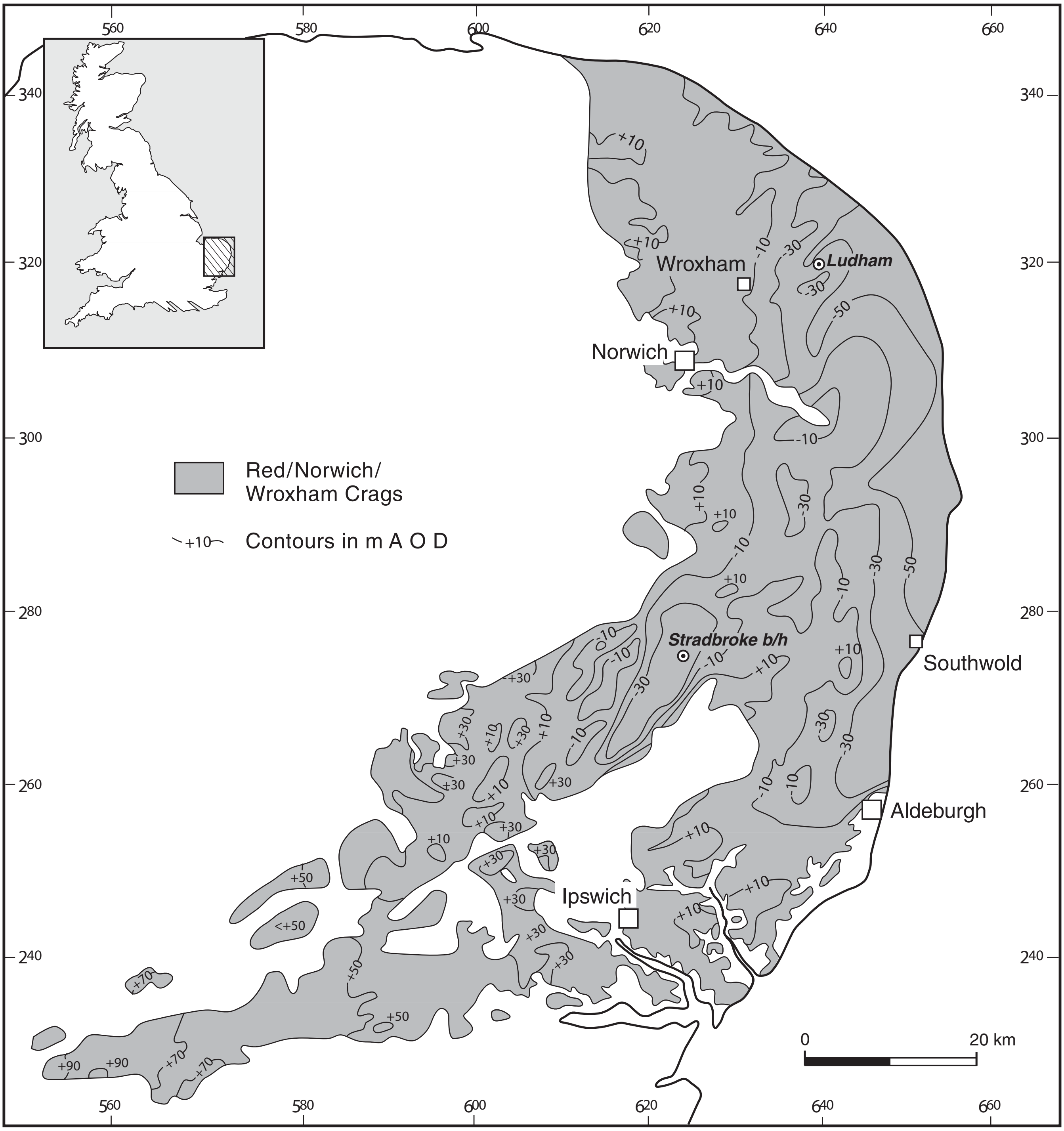

Figure 3.1 Distribution of the Red Crag, Norwich Crag, and Wroxham Crag in East Anglia, with contours on the base. From a variety of sources listed in Zalasiewicz et al. (1988).

but there is continuing confusion about the Red Crag–Norwich Crag boundary. In the following sections, the practice of Hamblin et al. (1997) and Moorlock et al. (in press) in the Lowestoft/Saxmundham memoir is followed.

The overall thickness of the Crag is not known to exceed 70 m on land, although it must originally have been much greater, since the greatest recorded thickness (69.5 m at the Stradbroke Borehole) is wholly Red Crag.

Cementation of the Crag is variable. The Coralline Crag has a calcite cement, derived from the dissolution of aragonitic shell debris. The Red, Norwich and Wroxham crags are commonly decalcified. At depth they are generally uncemented, but in the weathered zone there is strong but patchy/lenticular ferruginous cementation derived from the weathering of glauconite. The Environment Agency reports that numerous drillers logs refer to cementation at depth, and Funnell and Booth (1983) record hard, cemented nodules and bands of sand and clay below 33 m in the Stradbroke Borehole.

Vertical or inclined fissures have been reported in exposures of both the Coralline and Red crags in a broad coastal tract, south of Aldeburgh, down to Walton-on-the-Naze (Balson and Humphreys, 1986). These are considered to be, in the most part, joints, and are probably the result of early Pleistocene tectonic flexuring, on the western margin of the subsiding North Sea Basin.

3.1.2 General hydrogeology

3.1.2.1 *Introduction*

The Crag has been variably described as: being an 'unpromising' aquifer (Clarke and Phillips, 1984); having 'high permeability' (Cox et al., 1989); and constituting a 'substantial, if complex, groundwater resource [together with younger Quaternary formations]' (Arthurton et al., 1994). In part these divergent opinions stem from the wide range of hydrogeological conditions represented by the Crag. These range from being part of a composite Chalk/Crag multi-aquifer unit, through partial confinement beneath Quaternary glacial/periglacial and alluvial deposits, to unconfined units above the Eocene strata. In general, the Crag is relatively permeable, although problems with well construction, due to the lack of cementation and wide grain size distribution, affect its use. Further problems are imposed by the high iron content of Crag water, and the aquifer's variability and complexity, especially where it is in hydraulic contact with other formations.

3.1.2.2 *Groundwater flow and recharge*

Groundwater flow in the Crag is intergranular, with yields depending on the coarseness of the sand and gravel fraction and on the degree of sorting. The flow system is controlled by the alternating layers of clays, silts and sands and their contrasting permeabilities (Hiscock, 1991). Although the clay layers probably have only limited lateral extent, the degree of continuity will obviously influence horizontal groundwater movement, and may give rise to aquifer layers (Holman, 1994).

The Crag is generally considered to be an unconfined aquifer, with recharge occurring over its whole extent (Hiscock, 1991; Holman, 1994), although some work has suggested that marsh areas may be an exception (Holman, 1994).

Drainage of marshland below sea level has resulted in river systems standing above the level of the surrounding land. These surface water bodies have the potential to be sites of significant recharge, although the water is brackish (Holman, 1994). The lowering of Crag water levels below sea level by pumped drainage of the marshes (Hiscock, 1991) may also result in saline intrusion near the coast or tidal rivers.

In the west of the area, the Crag is directly underlain by the Chalk, with which it is in hydraulic continuity. However, the potentiometric surface in the Chalk tends to be lower than that in the Crag, and hence it is unlikely to provide any upward leakage to the latter. Rather the reverse may be the case in some areas, with the Crag providing an important contribution of recharge to the Chalk. To the east, where the Palaeogene clays restrict recharge to the Chalk, discharge may occur at valley sides or into marshland fringes (Arthurton et al., 1994).

3.1.2.3 *Nature and extent of confinement*

Where overlain by younger Quaternary formations, the combined Crag and younger formations can comprise a substantial, though complex, groundwater resource (Arthurton et al., 1994). However, this depends on the lithology of the overlying drift; where deposits have a high clay content, they may act as a semi-confining layer, or restrict recharge to the aquifer (Holman, 1994). In some cases, leakage to the Crag may occur from perched aquifers in the drift deposits. For example the Corton Formation includes alternating sands and semi-permeable tills which may allow leakage from the sands through to the Crag (Price and Tuson, 1961; Holman, 1994).

There is also some degree of confinement within the Crag. Holman (1994) identified two clay layers within the Crag at Ludham which may be laterally continuous and suggested that one of the clay layers at Ludham could be acting as a laterally continuous aquitard. This would indicate that it may be more appropriate there to consider the Crag aquifer as a multi-aquifer system of at least two layers. Other minor clay and silt layers further add to the Crags' hydraulic complexity. The negligible nitrate concentrations and low tritium values recorded at Ludham suggest that the clay layers could be important in restricting the downward movement of modern recharge and any associated contaminants.

3.1.2.4 *Effects of overlying/underlying deposits*

In west Norfolk, the Crag is in hydraulic continuity with the underlying Chalk. In the east, it is separated from the Chalk by the Palaeogene clay formations, and potentiometric surface elevations are higher than those in the Chalk (Arthurton et al., 1994). A study carried out at Rushall in south Norfolk (Foster and Robertson, 1977) suggested that even to the west of the limit of Palaeogene clays, the development of putty chalk (a glacial cryoturbation product) could restrict movement of water between the Crag and Chalk. Leakage did occur when the head difference was sufficient, which was proven by the fact that water levels in the Crag responded to pumping in a similar way to those in the Chalk, except to a lesser degree and less rapidly. This leakage was considered to be the cause of the rapid equilibrium of pumping water levels in the Chalk, and it was considered that higher abstraction rates could be sustained in the short and medium term because of the large volume of water in storage in the overlying Crag and glacial deposits, the latter acting as an important storage reservoir.

It is reported that there is little hydraulic connection between the Chalk and Crag in the Stradbroke depression (P Willett, personal communication). In the east, Palaeogene clays beneath the Crag provide an effective base to the aquifer, and isolate it from the Chalk.

3.1.2.5 *Previous studies*

As noted by Price and Tuson (1961), much has been written on the Pleistocene and Neogene stratigraphy of East Anglia; however, with regard to the groundwater resources of the same deposits, very little has ever been published. Most of the published work has been carried out on specific areas, often as an ancillary part of a study of the Chalk. Some work has been carried out around Sizewell in Suffolk (Erskine, 1991), and in parts of the Thurne catchment (Holman, 1994). A general overview of the use of the Crags as a source of water is given by Clarke and Phillips (1984).

3.1.3 Aquifer properties data availability

Aquifer properties data were largely obtained from EA licensing records, pumping test files, and reports. Nearly 180 values of transmissivity were obtained, and 140 values of storage coefficient. There is likely to have been some misclassification of formations, both within the Crag, and between the Crag and younger deposits. For example, Clarke and Phillips (1984) highlight the difficulty in separating the Crag from overlying glacial sands in the absence of fossils.

Some data collected for this project were classified as 'crag and/or gravels' or other superficial deposits. Due to the problem of deciding whether the resultant test values were Crag, later Quaternary, or the two aquifers combined, these were eventually removed from the statistical analysis, although they remain as entries in the database. Subdivision of the Crag was not possible: out of 213 data points, only one was classified as Coralline Crag, seven as Red Crag, and seven as Norwich Crag. Therefore, all have been grouped together for the purpose of analysis.

Five core samples are entered on the database in East Anglia for two sites classified as Pliocene and Pleistocene respectively. Only the former appear to be Crag data.

3.1.4 General aquifer properties

Groundwater flow is matrix dominated. Reasonable yields are achievable, and some high values of yield, specific capacity and transmissivity have been recorded. However, the yields depend not only on the lithological variation and its effect on aquifer properties, but also on borehole construction (see Section 3.2.3.1).

3.2 THE CRAG OF EAST ANGLIA

3.2.1 Introduction

As described earlier, the Crag is subdivided into the Coralline Crag, Red Crag, Norwich Crag and Wroxham Crag. These are described individually in terms of their geology, although it has not been possible to differentiate the hydrogeological characteristics of the different formations.

3.2.2 Geology and stratigraphy

3.2.2.1 *Coralline Crag*

Distribution

The Coralline Crag is restricted to an area around Aldeburgh (see Figure 3.2). It rests unconformably on London Clay, and is overlain unconformably by Red Crag. It crops out around Aldeburgh and northwards to the headland of Thorpeness.

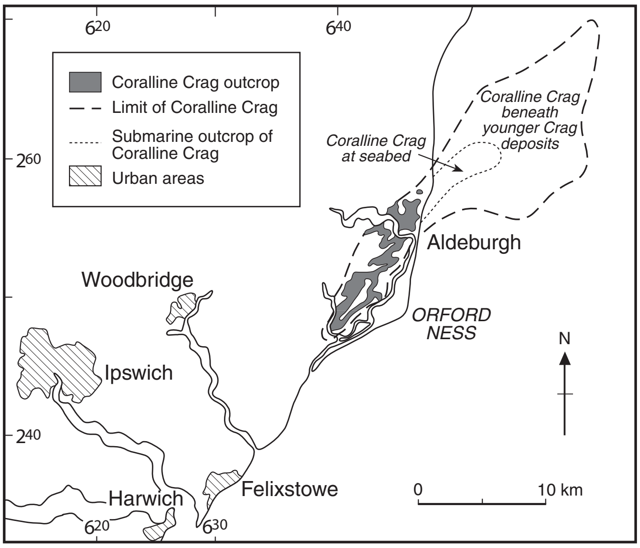

Figure 3.2 Distribution of the Coralline Crag, after Mathers et al. (1984).

Nomenclature

The Coralline Crag was so named by Charlesworth (1835) and no alternative names have been used subsequently. There are three members: the Ramsholt, Sudbourne and Aldeburgh members (Balson et al., 1993).

Lithology and stratigraphy

The total thickness is estimated as 25 m (Moorlock et al., in press) although the maximum recorded thickness is 15.5 m in boreholes north of Aldeburgh. The deposits are the deepest-water formation of the Crags, and comprise carbonate-rich skeletal sands. Most of the sand fraction comprises calcitic debris derived from bryozoans and calcitic mollusc debris. The aragonitic molluscs have been dissolved out and many of the fossils are unbroken; corals are rare. Insoluble sand and mud make up around 10% of the formation. Faint gently-dipping bedding planes imply cross-bedded sets up to 30 cm thick. There are lag-deposit gravels characterised by pebbles of phosphatised mudstone (Balson, 1989).

3.2.2.2 *Red Crag*

Distribution

The Red Crag is only seen at outcrop southwards from the latitude of Aldeburgh, but it occurs at least as far north as Ludham. It appears to be restricted to three north-east-trending basins:

- one extending from Southwold in the north-east, south and west of Aldeburgh
- the Stradbroke Trough (Funnell, 1972) passing through the Stradbroke Borehole and Bungay (see Figure 3.1)
- one passing through Ludham.

The shape of the Ludham basin is not known owing to a lack of boreholes penetrating the base, but the other two are asymmetric, with steep south-east flanks and shallow north-west flanks (see Figure 3.1). The form of the basins suggests that they were tectonically formed, with faults on their south-east flanks, and it has been suggested that the Red Crag was deposited penecontemporaneously with the down-faulting and folding (Bristow, 1983; Hamblin et al., 1997). This is supported by the difference in sedimentology between Aldeburgh and Stradbroke. It has alternatively been suggested that the basins were formed by erosion before the deposition of the Crag (Zalasiewicz et al., 1988), or by tidal scour (Funnell 1972). Figure 3.3 shows cross-sections and their trace from the Stradbroke Borehole [TM 232 738] south-eastwards to Aldeburgh and eastwards to Southwold. These illustrate the preservation of the Red Crag beneath the Norwich Crag (sub-Antian/Bramertonian unconformity).

The absolute geographical extent of the Red Crag is not known since north of Aldeburgh it is everywhere overlain by the Norwich Crag, but it may be assumed that the three basins deepen north-eastwards and possibly combine at depth. South-westwards from Aldeburgh and Stradbroke, Bristow (1983) found it impossible to differentiate the Red and Norwich crags by conventional mapping, but considered the deposits there to be mostly Red Crag.

Nomenclature

The Red Crag was named by Charlesworth (1835). Around Aldeburgh it is sub-divided into Sizewell and Thorpeness members, while the Red Crag strata in the Ludham Borehole have been referred to as Ludham Crag.

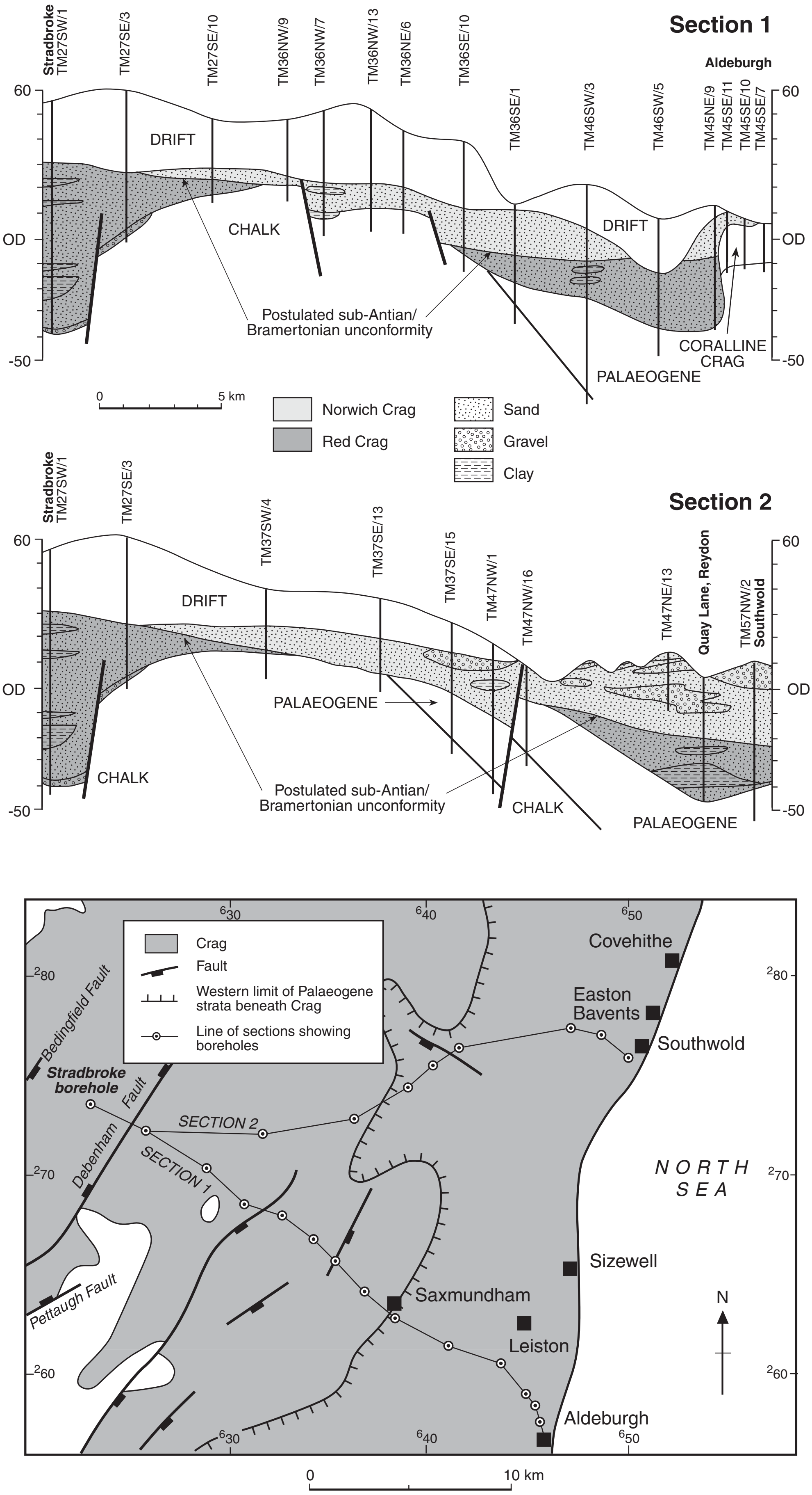

Figure 3.3 Cross-sections and their trace illustrating the relationships between Crag and other strata, and the preservation of the Red Crag beneath the Norwich Crag (from Hamblin et al., 1997).

Lithology and stratigraphy

Where the Red Crag rests upon the Chalk there is commonly a basal bed up to 2 m thick of glauconite-coated rolled flints, representing a transgressive gravel beach deposit. Where the Red Crag overlies Palaeogene strata, the basal bed commonly contains a high proportion of phosphate pebbles (Dixon, 1979; Bristow, 1983). Above this, in the Aldeburgh area, the Red Crag comprises poorly-sorted, cross-bedded, medium- to coarse-grained shelly sands, coarsening upwards. The Sizewell Member comprises 13 m of medium- and coarse-grained, moderately- to poorly-sorted greyish-green (glauconitic) shelly sands interbedded with clays containing silt and sand laminae. The Thorpeness Member, 20 to 30 m thick, comprises two upward-coarsening cycles of shelly fine- to medium- and rarely coarse-grained sands, including a few silty laminae, fragmented molluscan material, silty clay rip-up clasts and rare phosphate pebbles.

In the Stradbroke Trough, the Stradbroke Borehole revealed 69.5 m of Red Crag, dominantly green and grey sands, coarse and shelly at depth, but becoming fine-grained above. The sands contained clay bodies throughout their thickness, including one up to 9.9 m thick, as well as 'claystone' nodules (Funnell and Booth, 1983).

In the Ludham trough, the Red Crag is known from boreholes at Ludham [TG 385 199] and Ormesby [TG 5145 1425]. At the former, the thickness of the Red Crag totalled about 30.8 m. From the base, this comprised 1.8 m of grey shelly sands with black flints up to 8 cm in diameter, 22.0 m of grey shelly sands with thin clay seams lower down and 1.8 m of grey shelly silty clay at the top, and 7.0 m of grey silty clays with subordinate shelly sands. At Ormesby, 24.7 m of Red Crag comprised 10.4 m of bioturbated, glauconitic, coarse-grained sands with abundant comminuted shell debris, overlain by olive-grey finely laminated clay interbedded with cross-bedded, glauconitic shelly sand, overlain in turn by 14.3 m of finely interlayered sand and mud, and flaser- and lenticular-bedded clay, silt and fine-grained sand, with common glauconite and mica.

3.2.2.3 *Norwich Crag*

Distribution

The Norwich Crag forms a uniform sheet of strata around 30 m thick, dipping gently north-eastwards in Norfolk and Suffolk. It is not clear how much is present south-west of Aldeburgh, although it is probably not great. The strata occur across the Saxmundham and Lowestoft sheets, with the Wroxham Crag overlying it locally north of Southwold. It is present as far north as Norwich and Ludham, but it is not clear how rapidly it disappears beneath the Wroxham Formation beyond that: it does not reach Wroxham or the North Norfolk Coast. The Norwich Crag rests unconformably on Red Crag where that is present; elsewhere it lies unconformably on Palaeogene or Upper Chalk strata (e.g. at Bramerton near Norwich). The relations are complex, as is illustrated by Figure 3.3.

Nomenclature

The Norwich Crag was named the Mammeliferous Crag by Charlesworth (1835), and renamed the Norwich or Fluvio-Marine Crag by Lyell (1839). The term Norwich Crag became accepted, although the term Icenian Crag, proposed by Harmer (1898; 1900) is still used as a synonym. The Great Yarmouth Memoir (Arthurton et al., 1994) dropped formational terms and referred to the Norwich Crag as simply Crag Group, but Hamblin et al. (1997) re-introduced the Norwich Crag as a formation and this is now the accepted term.

Various local or 'member' names have been used, including Chillesford Sand, Creeting Sand, Chillesford Clay, Eaton Bavents Clay, and Westleton Beds (gravels). Zalasiewicz and Mathers (1985) formalised the Chillesford Sand and the (overlying) Chillesford Clay members in the Aldeburgh district, but as it is not clear north of Aldeburgh how much of the Norwich Crag sands should be included in the Chillesford Sand, these are not distinguished on the 1:50 000 sheet (Saxmundham). There are a large number of gravel and clay bodies interbedded with Norwich Crag sands in the area between Dunwich and Benacre; all the gravels are by definition Westleton Beds, but only one of the clays would be the Eaton Bavents Clay, and hence the Easton Bavents Clay and the Westleton Beds are not considered to be members.

Lithology and stratigraphy

The Norwich Crag dominantly comprises fine- to medium-grained, micaceous sub-angular quartz sands, interbedded with clays. At depth the sands are highly glauconitic and dark green to black in colour, but at surface they are weathered orange by the oxidation of glauconite. Small-scale sedimentary structures include horizontal bedding, bipolar ripples, flaser bedding, isolated thin clay drapes, trough cross-sets up to 0.3 m high, vertical burrows, channel scours and polygonal mudcracks. Shell beds are common, particularly towards the base, but many more may possibly have been removed by decalcification.

The Chillesford Clay is an elliptical lenticular body of clay, approximately 12 km by 4 km, and is up to 5 m thick, outcropping in the Aldeburgh area. It comprises unfossiliferous pale to medium grey or buff silty clay, with scattered poorly defined laminae of silt and sand. Several clay lenses, lithologically similar and of approximately the same age (Baventian), occur along the coast from Easton Bavents to north of Covehithe, and at Thorington [TM 423 728] a clay body occurs sandwiched between gravels of the Westleton Beds. The thickest of these clay bodies, the Easton Bavents Clay, is less than 3 m thick.

A basal gravel of rolled flints commonly occurs where the Norwich Crag rests upon Chalk. Higher in the sequence the Westleton Beds comprise lenticles of gravel which are interpreted as regressive beach gravels (Hamblin et al., 1997). They are strongly concentrated in the area between Southwold, Halesworth and Dunwich Heath, where they form large-scale planar cross-stratified units in sets up to 10 m thick with foresets dipping south-eastwards. They are well sorted and dominated by well-rounded to sub-angular, chatter-marked high-sphericity flint pebbles and cobbles, with subordinate quartz and quartzite pebbles.

In the Ludham area the Norwich Crag is known from the Ludham and Ormesby boreholes. In the former it is about 19.5 m thick and comprises mostly grey and pale brown shelly fine- to coarse-grained sands with scattered clay seams and beds of rolled flint pebbles; it includes a 4.7 m band of grey silty clays with sandy partings and shell fragments. At Ormesby it is 31.4 m thick, and comprises well-sorted medium-grained micaceous glauconitic sands with thin clay drapes over ripples, and thick beds of flaser- and lenticular-bedded micaceous clay.

3.2.2.4 *Wroxham Crag*

Distribution

The Wroxham Crag forms a gently north-eastward dipping sheet which rests unconformably on the Norwich Crag at

Ludham and Ormesby, and cuts down to the west and north to rest on the Upper Chalk at Wroxham and the North Norfolk coast. It attains a maximum thickness of around 20 m around Wroxham, and thins northwards and eastwards. North of Wroxham, all of the Crag beneath the surface deposits is Wroxham Crag. Further south, on the Norwich and Great Yarmouth 1:50 000 geology sheets, it is believed that most of the Crag present at depth is Wroxham Formation, although it has not been mapped out. Further south again, on the Lowestoft sheet there is certainly some Wroxham Crag but again it has not been mapped. The Wroxham Crag probably extends as far south as Southwold.

Terminology

In the past the lower part of the Wroxham Crag would have been shown as Norwich Crag and the upper part as Cromer Forest-bed Formation. Local names include Bure Valley Beds (in the Bure Valley around Wroxham) and Weybourne Crag (on the north coast of Norfolk).

Lithology and stratigraphy

The Wroxham Crag comprises a complex of coarse sands, gravels and clays, as in the Norwich Crag, but on the whole is more intimately interbedded than the Norwich Crag. It has not been possible to map out gravel or clay bodies separately from the sands. The sands of the Wroxham Crag may be rather coarser-grained and possibly not quite so well sorted as those of the Red Crag. As with the Red and Norwich crags the sands are green and uncemented at depth, but orange to red in colour, and iron-cemented in the near-surface weathering zone. The Wroxham Crag is considered to include all the Crag which has a significant proportion of far-travelled pebbles in its gravel fraction

Gravels are an important constituent of the Wroxham Crag and as in the Westleton Beds of the Norwich Crag, these are dominated by well rounded, high sphericity, chatter-marked flint cobbles and pebbles up to 20 cm long. Unlike the Westleton Beds, up to around 30% of the pebbles are of quartz and quartzite. There is commonly a basal bed of glauconite-coated flints which are not heavily abraded and still have distinct white patinas and black cortices. Clay bodies are also important throughout the sequence and may be up to 4 m thick.

3.2.3 Hydrogeology

3.2.3.1 *Introduction*

The Crag aquifer covers a large part of the eastern region of East Anglia, although its development as a groundwater resource in its own right has been limited. It is most significant in the east, where the Chalk is confined beneath the London Clay and may contain highly saline, connate groundwater (Monkhouse and Richards, 1984; Holman, 1994), and here it supplies local, mostly agricultural and horticultural demand.

The main problems in utilising the Crag are due to:

- the unconsolidated nature and poor sorting of the deposits, resulting in sand ingress into wells constructed to inadequate designs
- variable and unpredictable yields
- high iron content of the water (both dissolved and suspended), resulting in iron deposition in pipelines
- other water quality problems, including manganese and nitrate.

The problems of well construction in the poorly consolidated deposits of the Crag are well known. For example, Cox et al. (1989) reported that, in spite of the high permeability of the sands and gravels of the Norwich Crag, the formation has been little used in the Norwich area due to well construction problems. In part this may have been due in the past to inapt construction methods (because unlike the adjacent Chalk aquifer, the deposits are only loosely consolidated and may need support during drilling) and inadequate designs (individual beds are often only poorly sorted, with significant proportion of fines). A typical suite of grain size analyses from five depth intervals within the Norwich Crag at Ludham (see Figure 3.4) shows that at this location, between a quarter and a third of the formation comprises material sized below fine sand (threshold size of 0.25 mm), and that much of it may comprise low density, easily mobilised fine shell fragments (Forbes, 1952). Entrained sediment measurements during step-pumping of the borehole demonstrated that the problem of sand ingress could be minimised by a combination of careful design of pack and abstraction regime. For this particular well a stable yield of 2600 m^3/d was possible.

Appropriate drilling techniques are reported to have produced in recent years a number of successful and efficient boreholes in the Crag (A Bannister and T Beddows, personal communication). Such techniques include the use of pull-back methods (to telescope screens inside casing), and careful well design e.g. applying suitable pack design criteria, and the use of materials designed to retain poorly-sorted sands with a high fines content, such as 0.250 mm and 0.150 mm geotextile-wrapped screen.

The problems with iron deposition are significant. Clarke and Phillips (1984) reported that boreholes could be rehabilitated by acidisation and should be constructed to be able to withstand such treatment without deterioration. Iron removal techniques would also be required near the well-head in order to prevent iron encrustation in pipelines.

Other water quality problems have been reported. Mathers et al. (1984) suggested that the water may be inadequate for domestic potable purposes without some treatment due to high manganese and hydrogen sulphide concentrations, these being more difficult to remove than iron.

Crag water may also be high in nitrates, although this is not always of recent origin (Hiscock, 1991), and historical analyses from the beginning of the present century show that even then, some sources had high nitrates. However,

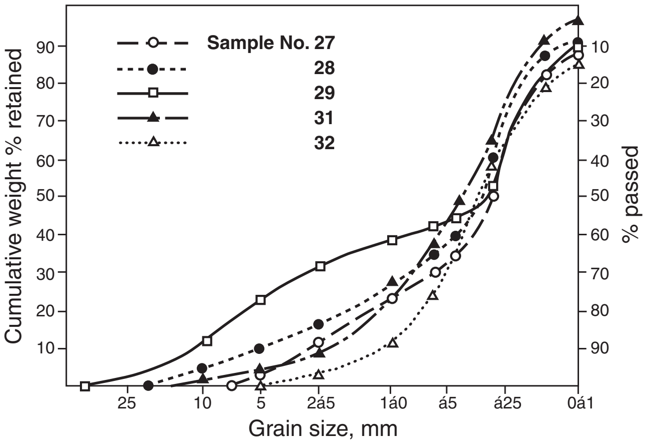

Figure 3.4 Sediment size analysis for Norwich Crag samples from a borehole at Ludham, Norfolk (from Forbes, 1952).

shallow wells do have a more recent input from agricultural practices. The interlayers of clay and silt may restrict downward movement of such pollutants in some areas. For example at Ludham [TG 385 199], water abstracted from the basal 6 m of the aquifer has a negligible nitrate content (Arthurton et al., 1994), implying relatively slow flow systems and long residence times. Overlying Pleistocene deposits may also be instrumental in reducing recharge.

Hardness of the Crag water at outcrop is around 300 mg/l, although this increases significantly beneath till (P Hiscock, 1991; Arthurton et al., 1994).

There is little that can be concluded about the hydrogeology of individual Crag members from the data collected for this project, largely due to the lack of detailed stratigraphy attached to borehole and pumping test records. The following, limited conclusions have been drawn mainly from their lithological properties.

Coralline Crag

The porosity of the Coralline Crag has been irregularly developed by dissolution, and porosity variations are not easily predicted (Anon. 1990). Where highly developed, porosity may exceptionally reach up to 60% (P Willett, personal communication,) and the Coralline Crag should be a hydrogeologically useful unit. However, such porosity development may be very localised.

Red Crag

The upper member of the Red Crag, the Thorpeness (also termed the Ludham) Member, has few clay lenses compared to the underlying Sizewell Member, and may be high yielding provided the groundwater level lies within the unit. In the Suffolk area, the overlying sands and gravels tend not to be saturated, and therefore the water level is likely to be in the Red Crag (D Seccombe, personal communication). The Red Crag is less lithologically variable than the Norwich Crag, and therefore might be expected to have more predictable aquifer properties (P Willett, personal communication).

Norwich Crag

The Norwich Crag has high permeability, but lack of consolidation and the presence of fines have caused problems with well construction (Cox et al., 1989). Aquifer properties are reported to be very variable, with boreholes only 100 m apart sometimes having completely different yields and this unpredictability has further constrained its development for water supply purposes (D Seccombe, personal communication).

3.2.3.2 *Aquifer properties*

The Crag is generally considered to be unconfined, and test results may show the effects of delayed drainage (Holman, 1994). However, many tests have been of too short a duration to show delayed yield, which may only become obvious after 10 to 14 days, and calculated storage coefficients indicate confined conditions. Pumping test length is now required to be of 14 to 30 days duration in order to obtain a reliable estimate of storage coefficient (P Willett, personal communication). Furthermore, transmissivity values calculated from tests on well point systems may give anomalously high values of transmissivity (P Willett, personal communication).

3.2.3.3 *Core data*

There are three core sample results from a single site at Aldeburgh, so the data probably refer to the Coralline Crag. Mean permeability was 14.8 m/d and mean porosity was 54%. The latter figure must be regarded as of dubious validity given the lithological nature of the Crag.

3.2.3.4 *Pumping test results*

Monkhouse and Richards (1984) found only one value of transmissivity for the Crag: this was for a site at Billesford Hall [TM 437 601]. The transmissivity was 950 m^2/d, and storage coefficient was 5×10^{-3}. Holman (1994) carried out a survey of the Thurne catchment in north-east Norfolk, and recorded transmissivity values ranging from 150 m^2/d to 1100 m^2/d, with storage coefficients in the range 10^{-2} to 10^{-4}.

One hundred and seventy nine values of transmissivity were collected as part of the data collection exercise for this project. Some of these (18 in total) were results from tests carried out on well point systems, and were removed from the dataset used for the statistical summaries. One hundred and forty values of storage coefficient were available, and 96 values of specific capacity. The results are summarised in Table 3.2.

Table 3.2 Summary of aquifer properties data for the East Anglian Crag.

All Crag records		
Total number of records	241	—
Number of transmissivity records	179	—
Minimum/maximum transmissivity value (m^2/d)	1.75	4231
Arithmetic/geometric mean of transmissivity (m^2/d)	605	394
Median/interquartile range of transmissivity (m^2/d)	412	533
25/75 percentile of transmissivity (m^2/d)	238	772
Number of storage coefficient values	140	—
Minimum/maximum storage coefficient value	7.0×10^{-5}	6.2×10^{-1}
Arithmetic/geometric mean of storage coefficient values	7.5×10^{-2}	2.0×10^{-2}
Median/interquartile range of storage coefficient values	4.0×10^{-2}	1.1×10^{-1}
25/75 percentile of storage coefficient values	4.1×10^{-3}	1.1×10^{-1}
Number of specific capacity values (m^3/d/m)	96	—
Minimum/maximum specific capacity value (m^3/d/m)	3.7	3413
Arithmetic/geometric mean of specific capacity values (m^3/d/m)	279	114
Median/interquartile range of specific capacity values (m^3/d/m)	107	208
25/75 percentile of specific capacity values (m^3/d/m)	40.5	249

The results show a considerable range in transmissivity, from 1.75 m^2/d to over 4200 m^2/d. However, the mean transmissivity of 605 m^2/d and interquartile range between 238 and 772 m^2/d of such a large dataset, shows that the Crag is quite consistently a productive aquifer. This is an important feature of the aquifer in its own right and also of its role as a storage medium for the Chalk where the Crag overlies it. Specific capacities can be similarly high, with a mean of more than 275 m^3/d/m, and interquartile range of 41 to 249 m^3/d/m. The results are plotted in Figures 3.5 and 3.7 respectively. Both show approximately log-normal distributions.

Storage coefficients vary from 7×10^{-5} to the (probably spurious value of) 0.61, with an interquartile range of 0.004 to 0.11 (see Figure 3.6); these values indicate unconfined to semi-confined conditions. Mean porosity has been estimated from electrical resistivity soundings to be between approximately 25% and 40% (Holman, 1994), although (P Willett, personal communication) suggested the porosity of the Coralline Crag may exceptionally be as high as 60%. With porosities in this range, the storage coefficients (equivalent to specific yield for unconfined aquifers) would be expected to be higher. The generally low values could indicate poor sorting of the aquifer, with relatively small pore spaces and pore neck apertures, leading to poor gravity drainage of the aquifer. It is also likely that some low values are due to the pumping tests being too short, with analysis being carried out on early time data which more closely reflects a confined value of storage coefficient, rather than the true specific yield.

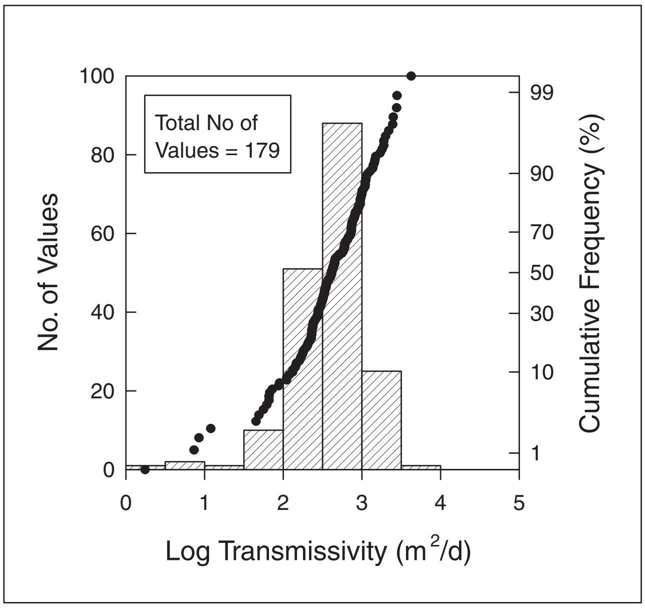

Figure 3.5 Distribution of transmissivity values from pumping tests in the Crag of East Anglia.

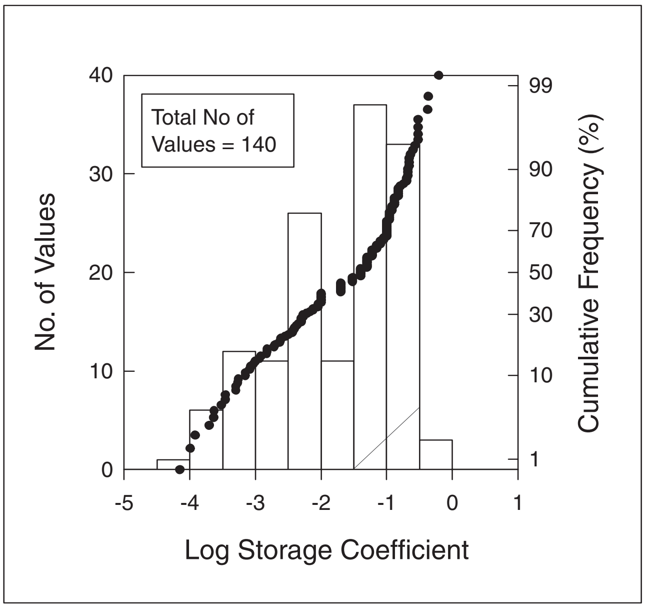

Figure 3.6 Distribution of storage coefficient values from pumping tests in the Crag of East Anglia.

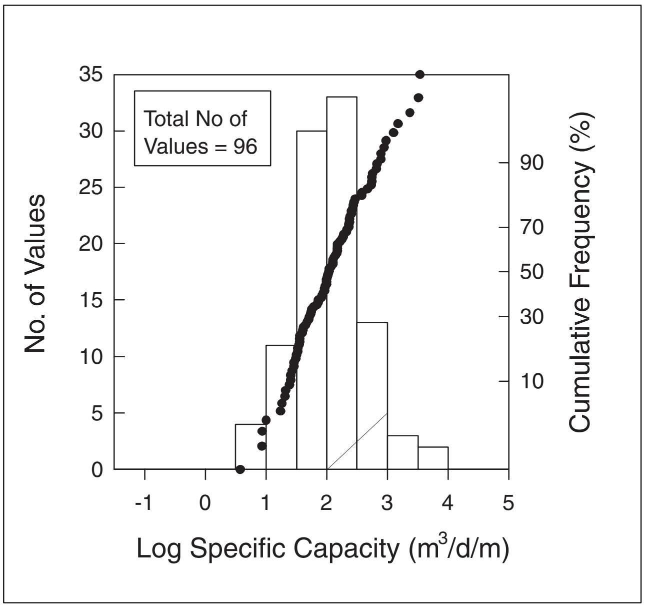

Figure 3.7 Distribution of specific capacity values from pumping tests in the Crag of East Anglia.

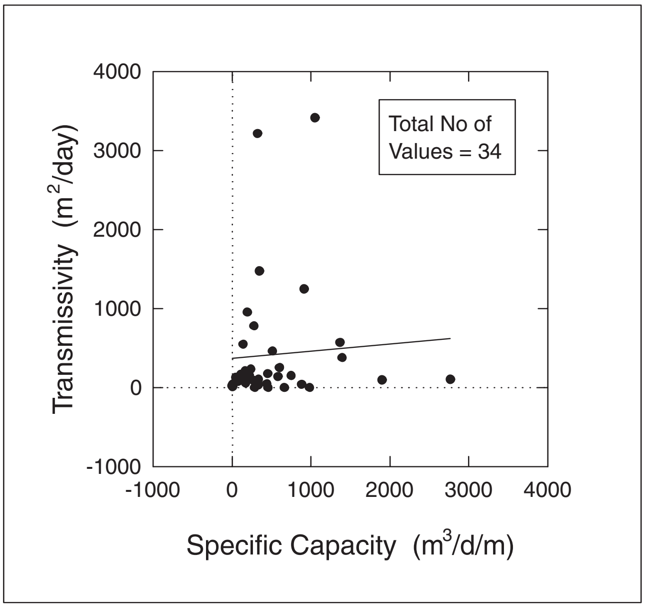

Figure 3.8 Correlation between transmissivity and specific capacity for the Crag of East Anglia.

There is a poor correlation between transmissivity and specific capacity, with considerable scatter of the data and an r^2 error of 0.0045 (see Figure 3.8). However, specific capacity is influenced by numerous factors, such as partial penetration effects, borehole diameter, well efficiency, position of the pump intake, and duration of pumping, which could partly explain the lack of correlation. In particular, it has been noted that the type of borehole construction strongly influences well efficiencies in the Crag (see Section 3.2.3.1), which is thought to explain the variation in yields, and could also possibly explain the lack of correlation between specific capacity and transmissivity.

3.2.3.5 *Yield data*

Yields from Crag boreholes are reportedly less dependable than the Chalk (Hiscock, 1991; Arthurton et al., 1994). However, borehole construction strongly influences well efficiencies and therefore yields, which may partially explain their variability. Three types of construction have been used:

- dug wells
- gravel packed or screened boreholes
- well point systems.

Older dug wells and collector systems tend to be shallow and of simple construction, and sand entry can be a problem. Such systems typically have low yields; Hiscock (1991) suggests pumping rates of 170 to 340 m^3/d are achievable. Well point systems have been used almost exclusively for spray irrigation (Holman, 1994); these consist of a series of narrow diameter perforated tubes connected by a suction header to a single pump. The yield of the system will depend partly on the number of well points (Arthurton et al., 1994). Yields from individual well points vary from 50 to 70 m^3/d (Holman, 1994), and a yield of around 780 m^3/d was achieved at Blofield [TG 330 122] with a system of 12 70 mm diameter, 6 m deep wells (Arthurton et al., 1994).

Much higher yields may be attained from soundly-designed boreholes using well-designed packs or geotextile-screened liners, although where sunk into finer grained sands, these will still be low. A test carried out at Ludham Pumping Station gave a yield of 3400 m^3/d for a drawdown of 11.9 m (Hiscock, 1991; Arthurton et al., 1994), equivalent to a very high specific capacity of 286 $m^3/d/m$. Monkhouse and Richards (1984) suggest maximum yields are generally of the order of 1000 m^3/d, and average yields are much less, around 250 m^3/d. At high pumping rates, large amounts of sediment may be drawn into the borehole, and optimum rates may therefore be less than the maximum.

As shown in Table 3.2, yield data collected as part of this project varied between 30 and 5763 m^3/d. There did not appear to be any predictable regional variation of yields. However, the data do not take into account the different types of borehole construction, which could account for part of the variability and mask any pattern.

3.2.3.6 *Grain size distribution data*

Reference has already been made to the grain size distribution curves from sieved samples of the Ludham borehole in Forbes (1952) (Figure 3.4). This well taps the Norwich Crag and indicates a formation comprising fine to medium sand with a d_{50} of 0.3 to 0.45 mm and a moderately low uniformity coefficient around five. If the samples are typical of the Norwich Crag elsewhere, filter pack and screen apertures would need careful design to avoid pumping sand.

3.2.3.7 *Controls on permeability and transmissivity*

As mentioned in Section 3.2.3, the Crag is a complex aquifer with numerous clay and silt layers, and hence the vertical permeability is likely to be strongly influenced by the existence and lateral continuity of these layers. The anisotropy produced by such low permeability layers not only impedes vertical water movements from one horizon to another, but also reduces the effective thickness penetrated by production boreholes. Both adversely affect the yield potential of the Crag.

The lithological variation is also likely to exert a major control on transmissivity. Although there does not appear to be any systematic variation in transmissivity that could be correlated with lithology, similar to that observed in storage coefficient, a trend could be masked by the different types of borehole construction: shallow wells would only partially penetrate the aquifer, resulting in low values.

3.2.3.8 *Areal distribution of aquifer parameters*

Examination of transmissivity results across the region does not reveal any definite systematic variation, although there may be a slight increase to the south. However, Figure 3.9 shows a definite increase in storage coefficient in the southern part of the Crag outcrop compared to the north. It appears that many of the high storage values probably lie on the Red Crag in the Aldeburgh area, and also on the Coralline Crag south-west of Aldeburgh. This would appear to correlate with the described lithological variations as the Red Crag is reported to be slightly coarser grained than the Norwich Crag, and hence might be expected to be more free-draining. Although the Red Crag is overlain by Norwich Crag between Aldeburgh and Southwold, it is possible that boreholes still penetrate the Red Crag. Alternatively, the trend may simply be due to lithological variation, and unrelated to the Crag formation utilised. With the limited data available, it is not possibly to draw any firm conclusions.

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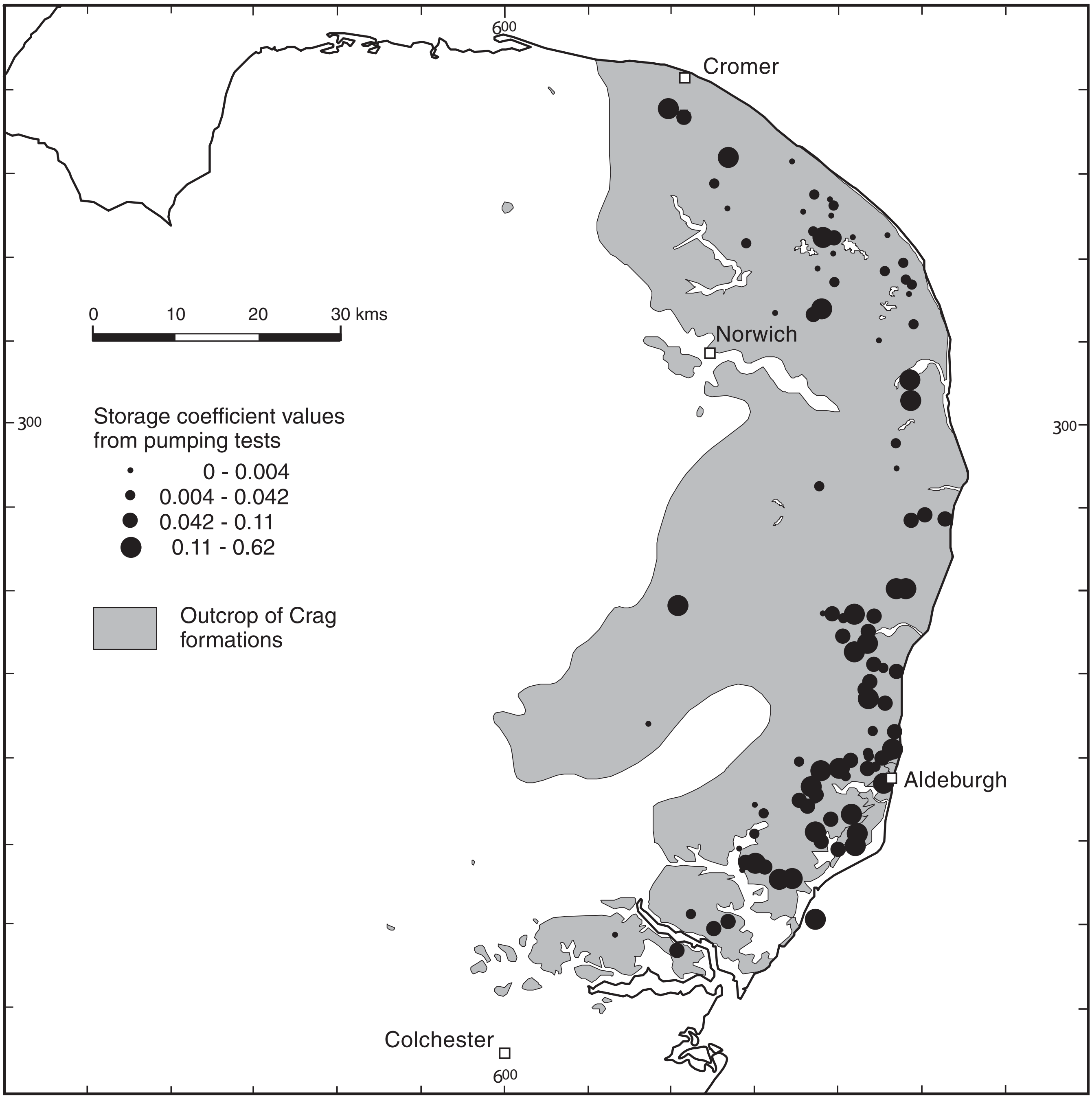

Figure 3.9 Regional distribution of storage coefficient values from pumping tests in the Crag of East Anglia.

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4 Palaeogene minor aquifers of the London and Hampshire basins

4.1 INTRODUCTION

The principal onshore outcrops of Palaeogene and Neogene beds in England and Wales are illustrated in Figure 4.1. The Crag, which comprises the main Neogene aquifer system, has already been described in the preceding chapter. In hydrogeological terms the principal Palaeogene formations of interest in England and Wales occur in the two relatively small synclinal areas of the London and Hampshire basins, and are described in this chapter.

4.1.1 General geology and stratigraphy

4.1.1.1 *Extent of aquifer groups*

The Palaeogene deposits of the London Basin referred to in this chapter, cover the lower parts of the Thames Valley and the fringes of the Thames Estuary. Their outcrop across the Hampshire Basin is bounded by a triangle with corners at Dorchester, Salisbury and Worthing, including the northern half of the Isle of Wight. Both of these outcrops have continuation seawards (Figure 4.1), the Hampshire Basin extending south-eastwards into the Dieppe Basin, and the London Basin forming part of the North Sea Basin.

4.1.1.2 *Stratigraphy and lithology*

Table 4.1 provides the most recent stratigraphic interpretation of the sequence and equivalence of the Palaeogene formations of the London and Hampshire basins (R Ellison, personal communication). Generalised cross-sections showing the lithological relationships of the Palaeogene beds in the London and Hampshire basins are shown in Figures 4.2 and 4.3 respectively. The nomenclature is complex, having undergone significant recent reclassification, but the sequence can be described essentially as a series of marine and estuarine sedimentary cycles. In Figure 4.2, the sequence above the London Clay Formation occurs mostly west of London, and the sequence below the London Clay Formation is between Berkshire and Kent. The lithologies and stratigraphy are described individually for the London and Hampshire basins in Sections 4.2.2 and 4.3.2 respectively.

4.1.1.3 *Depositional history*

Almost all the Palaeogene and Neogene strata were deposited in a shallow sea, probably occupying broad tidal estuaries or embayments, and brackish water lagoons. In this environment, periodic but relatively small changes in sea level, and minor tectonic movement, resulted in significant changes in sedimentation. As a consequence there are rapid vertical and lateral changes in many parts of the succession.

4.1.1.4 *Structural geology*

The Palaeogene deposits have been folded into synclinal basins and the strata generally dip towards the centres of the basins. Smaller scale structures have also been imposed on the beds by folding and minor faulting.

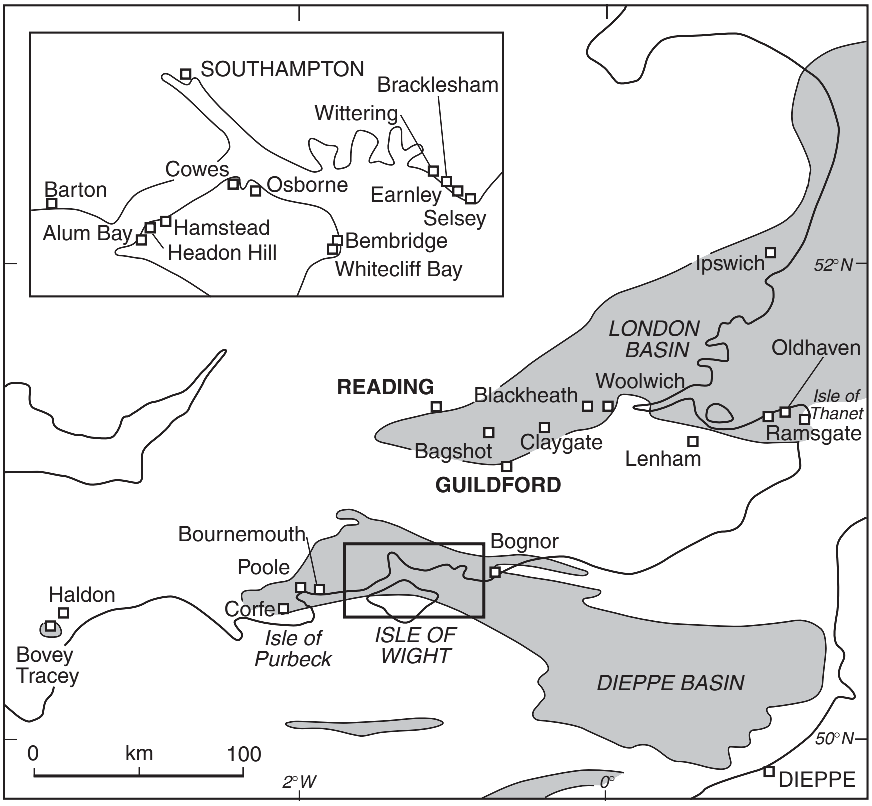
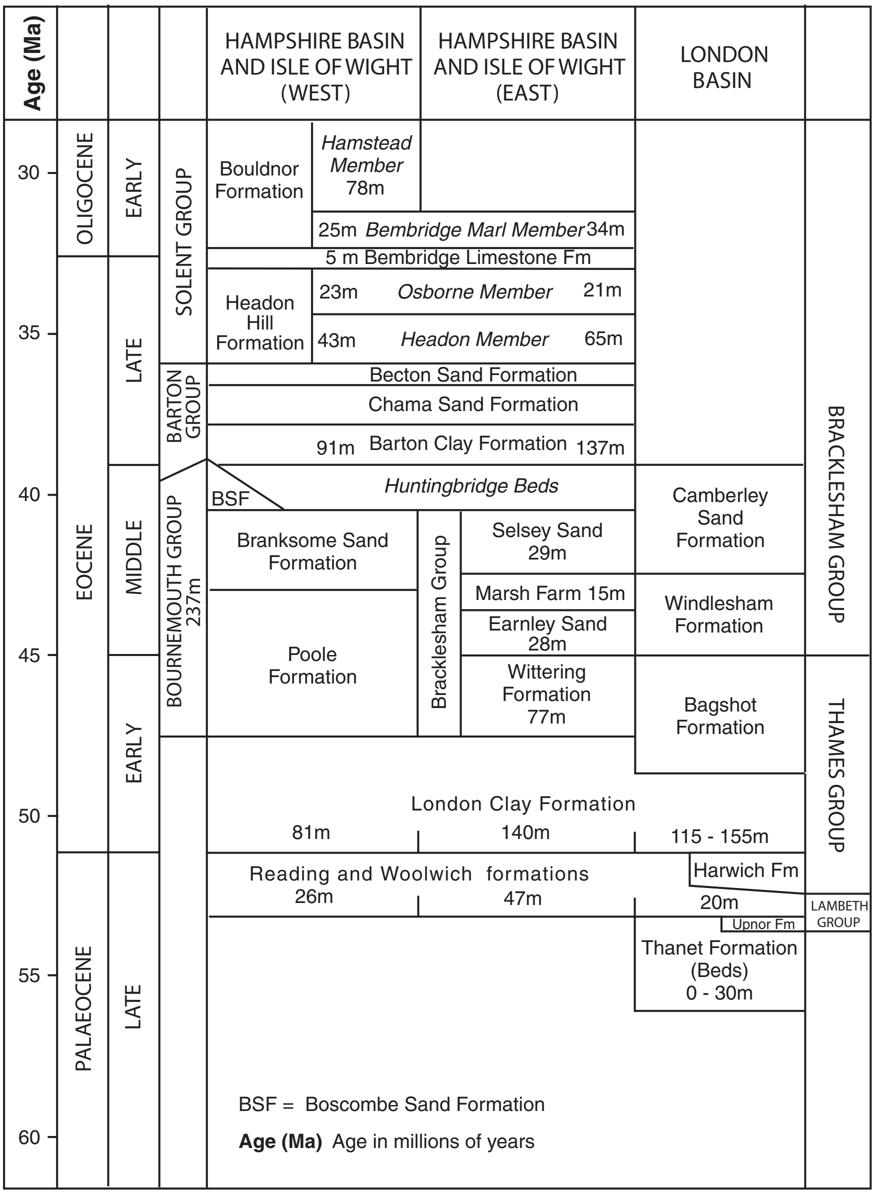


Figure 4.1 Outcrop of Palaeogene strata in southern England (from Curry, 1992).

Table 4.1 Outline stratigraphy and relationships of Palaeogene strata of the London and Hampshire basins (adapted from Curry, 1992).



4.1.2 General hydrogeology

4.1.2.1 *Controls on aquifer properties*

From a hydrogeological point of view there are few regionally significant minor aquifers. In Figures 4.2 and 4.3 the principal sand-dominated units which comprise the minor aquifers are shown in relation to the major clay-dominated aquitards/aquicludes. The great vertical and lateral variation of the more argillaceous units may also give rise to minor aquifers where sand lenses are present.

In many areas, oxidation and percolation of groundwater have weathered sand-dominated sequences to depths of several tens of metres, which is likely to increase the permeability. Perched water tables have also frequently led to the development of thin, irregular layers of iron-cemented sands. Their cementation would impede vertical leakage and may reduce the scope for recharge.

4.1.2.2 *Groundwater flow and recharge*

The regional pattern of groundwater flow in both major synclines is from the edge of the basin towards the centre. Local groundwater flow may be hard to predict, however, due to the lateral discontinuity of the sandy beds. Perched water tables are common.

4.1.2.3 *Effects of structures or igneous activity*

Faulting has local effects but is not a regional control on the Palaeogene minor aquifers, lithological controls being much more important. Igneous activity is not known to have any effect in the area. The effects of erosion on local fold structures can, however, have hydrogeological implications as they may further disrupt the continuity of sandy beds.

4.1.2.4 *Nature and extent of confinement*

As indicated in Figures 4.2 and 4.3, the sand-dominated minor aquifers are interlayered with clay-dominated aquitards. Many of the aquifers will therefore be confined or semi-confined by overlying clay beds. Lithological variations may also result in sandy layers within a formation being bounded laterally as well as vertically by clay layers. In particular, in the Hampshire Basin, the laterally discontinuous aquifers within the London Clay Formation such as the Whitecliff, Durley, Nursling and Portsmouth sands, are confined by the surrounding clay beds.

4.1.2.5 *Effects of overlying or underlying deposits*

Crag deposits of Neogene age disconformably overlie the Palaeogene sequence in north-east Essex. However, as they

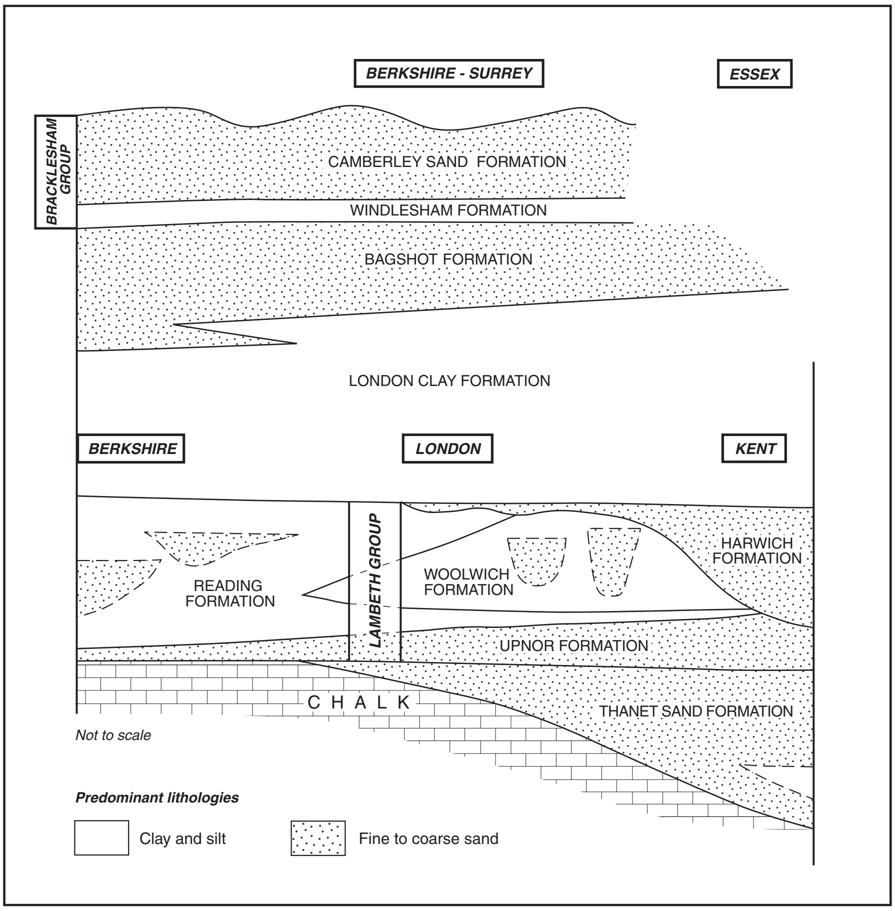


Figure 4.2 Relationship between Palaeogene minor aquifers in the London Basin (not to scale).

generally rest upon the London Clay Formation, the Crag aquifer system does not usually interact with the older Cainozoic (formerly referred to as Tertiary) aquifers.

Quaternary deposits are complex and are not described in detail here. In the London Basin, they are fluvial rather than glacial, although the tills of southern East Anglia do overstep the Chalk on to the Palaeogene strata. Where till is present, recharge to the Palaeogene minor aquifers may be restricted. Gravel deposits of the Thames and proto-Thames are used as aquifers, generally in preference to the underlying Palaeogene strata, although they are probably in hydraulic continuity.

In the Hampshire Basin, brickearth, plateau gravels or valley gravels overlie Palaeogene beds in some areas. Only the brickearth is likely inhibit recharge to the underlying minor aquifers.

Where the basal Palaeogene strata are arenaceous, the sands are in hydraulic continuity with the underlying Chalk, and the combined deposits are considered to be a single aquifer (see Section 4.2.3.1). The proportion of sand in these formations decreases to the west (see Figure 4.2). Where clay predominates, the Palaeogene deposits provide an aquitard of regional extent, and a useful element of additional drainable storage overlying the Chalk aquifer. North of Southampton, yields from the Reading Formation can be up to 200 m^3/d from boreholes, and this is thought to be partly due to upward recharge to the formation from the underlying Chalk. In the London Basin, over-abstraction early in this century led to dewatering of the sands, although they still continued to play a part in distributing water to the Chalk in certain areas of the basin.

4.1.2.6 *Previous studies*

There have been no major treatises or papers on the Palaeogene minor aquifers. However, a groundwater study of the London Basin (Water Resources Board, 1972) which focused mainly on the Chalk, also covered the hydrogeology of the Palaeogene strata beneath the London Clay Formation. Conclusions and data from this study are referred to where appropriate. Descriptions of the hydrogeology may also be found in Water Supply Memoirs (Buchan, 1938) and Geological Memoirs. Some local studies have also been undertaken as part of licence applications for boreholes abstracting from the aquifers.

4.1.3 Aquifer properties data availability

Data on aquifer properties are constrained by the limited usage of the aquifers. Eleven values of transmissivity were available for the London Basin, and only eight for the Hampshire Basin. For specific capacity there were rather more records: 35 and 43 respectively. Values for storage coefficient were very sparse, there being six values for each basin. More data were available for the Palaeocene aquifers, although the majority of these were obtained for a detailed study of the London Basin (Water Resources Board, 1972) and only cover this area (see below).

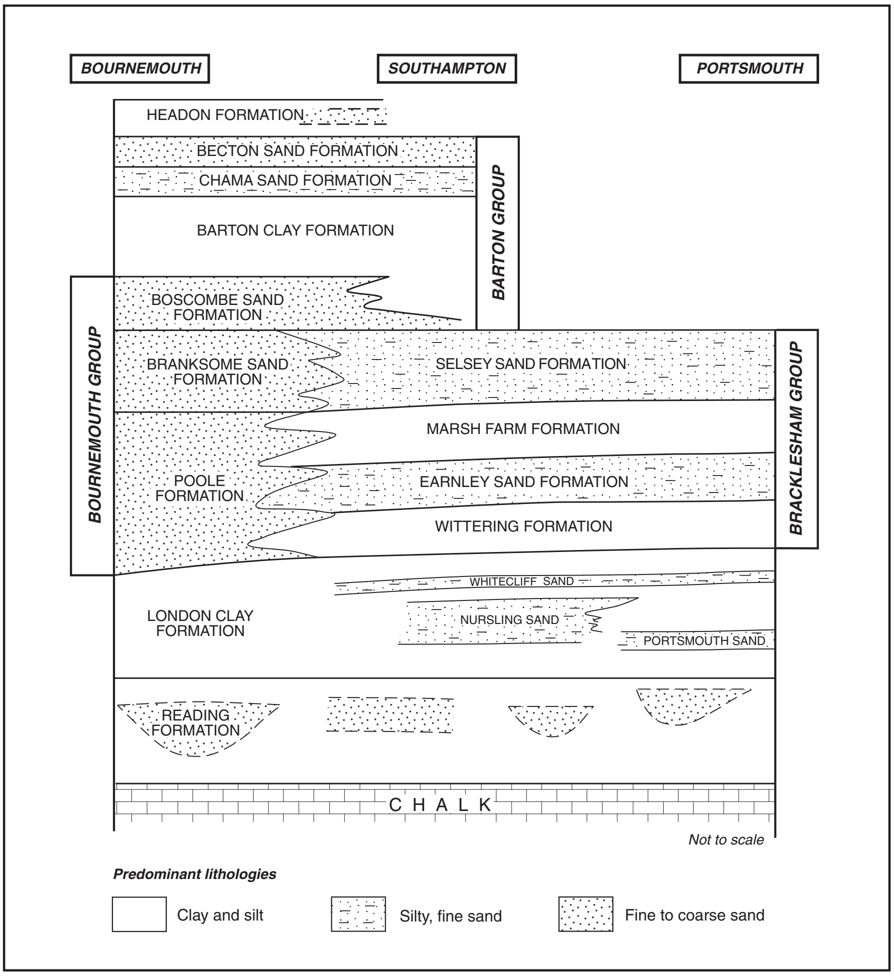
As the geological nomenclature of the Palaeogene Beds has been revised and updated in recent years, the data usually refer to aquifers as they were formerly known. The new terminology has been used in the following sections.

4.1.4 General aquifer properties

4.1.4.1 *Core data*

Permeability results are held in the Aquifer Properties Database for the Thanet, Reading and Woolwich, and Blackheath formations, together with 13 samples from one site classified only as Eocene. Therefore, only the Palaeocene aquifers are discussed in this section. To make the results statistically usable, data from both basins have been analysed

Figure 4.3 Relationship between Palaeogene minor aquifers in the Hampshire Basin (not to scale).



together. The results are summarised in Table 4.2 and illustrated in Figure 4.4.

Intergranular permeabilities are moderately high, with geometric means of all three formations in the range 2 to 6 m/d, and 75% of all samples greater than 0.9 m/d. Despite these reasonably high values of permeability, these formations are only classified as minor aquifers due to their moderate productivity. This, in turn is a result of

Table 4.2 Summary of hydraulic conductivity data from Palaeogene core samples.

Thanet Formation		
Total number of records	43	—
Number of hydraulic conductivity records	40	—
Minimum/maximum hydraulic conductivity value (m/d)	0.01	167
Arithmetic/geometric mean of hydraulic conductivity (m/d)	11.3	3.48
Median/interquartile range of hydraulic conductivity (m/d)	3.00	6.25
25/75 percentile of hydraulic conductivity (m/d)	1.70	7.95
Reading and Woolwich formations		
Total number of records	105	—
Number of hydraulic conductivity records	101	—
Minimum/maximum hydraulic conductivity value (m/d)	0.003	198
Arithmetic/geometric mean of hydraulic conductivity (m/d)	10.3	2.22
Median/interquartile range of hydraulic conductivity (m/d)	3.31	9.99
25/75 percentile of hydraulic conductivity (m/d)	0.91	10.9
Harwich Formation (Blackheath Beds)		
Total number of records	23	—
Number of hydraulic conductivity records	22	—
Minimum/maximum hydraulic conductivity value (m/d)	0.94	94.5
Arithmetic/geometric mean of hydraulic conductivity (m/d)	13.0	5.86
Median/interquartile range of hydraulic conductivity (m/d)	5.57	9.13
25/75 percentile of hydraulic conductivity (m/d)	2.34	11.5

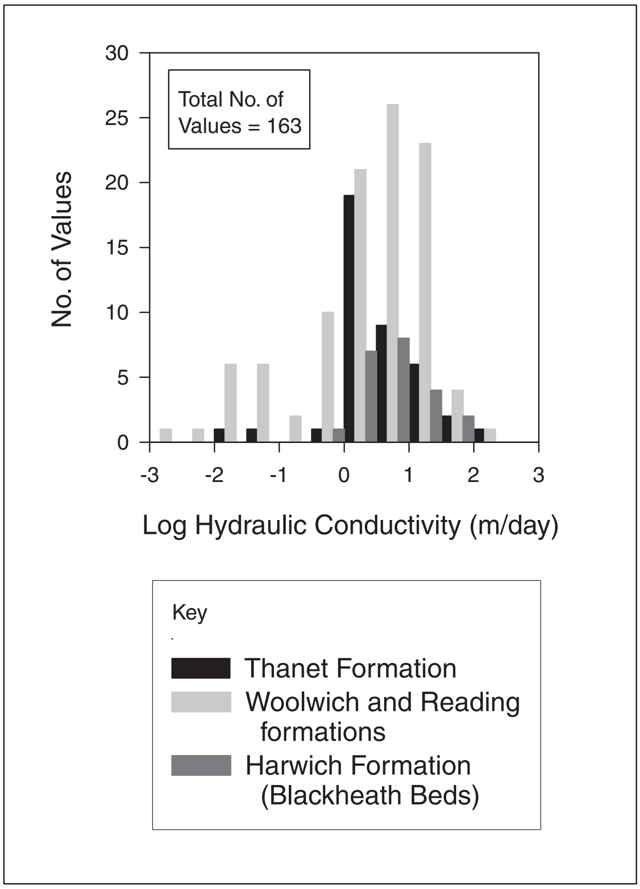


Figure 4.4 Comparison of hydraulic conductivity distribution in three formations of the Palaeogene of southern England.

three factors: limited saturated thickness; strong anisotropy as a result of silt/clay interbedding; and rapid changes in thickness and facies both along strike and down-dip, arising from the estuarine/shallow marine depositional environment.

Figure 4.4 indicates that there is little obvious difference in hydraulic conductivity between the Reading Beds facies and Harwich Formation.

4.1.4.2 *Pumping test data*

There are few pumping test results for the Palaeogene minor aquifers of the London and Hampshire basins, so all Palaeogene data has been aggregated for each basins except for specific capacity, where it has been possible to analyse the Bagshot Formation separately (see Section 4.4). It should be noted that many of the specific capacities are derived from well record catalogues, with old values. These may have altered with time, especially in the London Basin, due to falling and subsequent rising of regional water levels.

4.1.4.3 *Other sources of data*

Some information about yield and drawdown from wells and boreholes in the Palaeogene aquifers is available in the National Well Archive held by the British Geological Survey. The database of licensed abstractions held by the Environment Agency also provides some evidence for the yields obtainable from the different aquifers.

4.2 THE LONDON BASIN

4.2.1 Introduction

The London Basin is an asymmetrical syncline comprising Palaeogene deposits overlying the Chalk, which crops out in the Chiltern Hills to the north and the North Downs to the south. The basin extends westwards as far as Newbury and northwards to Ipswich. The maximum thickness of the Palaeogene strata within the London Basin is around 320 m, this being to the east of Camberley and Farnborough.

The London Basin is situated between the prominent chalk hills of the Chilterns and the North Downs. The topography within the basin is generally fairly subdued, being dominated by the floodplain of the Thames, although some minor topographic features occur.

4.2.2 Geology and stratigraphy

The Palaeogene strata of the London Basin are described below and their relationships illustrated in Figure 4.2.

4.2.2.1 *Lithology and stratigraphy*

Thanet Formation

The Thanet Formation occurs only in the London Basin, resting conformably on the Chalk. It consists of marine glauconitic clayey silts and fine sands, varying in thickness from a maximum of 40 m on the Isle of Sheppey, to around 30 m in north Kent, to zero near Guildford and Ipswich. The formation comprises fine-grained clays and silts to the east of Newington, coarsening to the west where the clays are replaced by fine-grained sands (Southern Water Authority, 1981).

Lambeth Group

The Lambeth Group includes the Upnor Formation and the Reading and Woolwich formations of previous classifications.

UPNOR FORMATION

The Upnor Formation, formerly the Woolwich Bottom Bed, forms the basal beds of the Lambeth Group. It comprises 5 to 6 m of medium-grained sands. Generally there is a basal conglomeratic layer containing rounded flint pebbles, but in the eastern part of the region the basal bed is locally absent, and it is difficult to distinguish the Upnor Formation from the underlying Thanet Formation.

READING AND WOOLWICH FORMATIONS

The Reading and Woolwich formations are of approximately lateral equivalence, and are present throughout both London and Hampshire basins. The Reading Formation is generally about 10 to 15 m thick in the London Basin, reaching a maximum of around 22 m at Chertsey. It forms a narrow outcrop at the northern and southern edges of the basin, and elsewhere is at depth beneath the London Clay Formation. Inliers occur in the Eton and Greenwich areas. There are also many small outcrops of the formation to the north of the basin. The main mass of the Woolwich Formation is typically developed along the north Kent coast and in south London. It comprises dark lagoonal or estuarine clays and sands. In the western half of the London Basin and in the Hampshire Basin the Woolwich Formation is replaced laterally by the red and variegated clays and associated dune-sands of the Reading Formation, although some interdigitation of the two facies occurs locally, particularly in central London. The Woolwich Formation reaches a maximum thickness of 10 m near Lewisham in south-east London.

Thames Group

The Thames Group includes the Harwich Formation, the London Clay Formation, and the Bagshot Formation.

HARWICH FORMATION

Overlying the Woolwich Formation in the south of the London Basin is a series of sands and flint-pebble beds, the Harwich Formation. The formation is made up of several distinct facies. In south London, it consists of cross-bedded sand with rounded flint pebbles, the Blackheath Beds, which are up to 12 m thick. To the east, in Essex and north Kent, the formation comprises the lithologically similar Oldhaven Beds, which are about 10 m thick in the Isle of Sheppey, but thin westwards, and are absent in central London.

The formations sandwiched between the Chalk and the London Clay Formation (the Thanet, Upnor, Woolwich and Reading, and Harwich formations) have previously been known collectively as the 'Lower London Tertiaries', or hydrogeologically as the 'Basal Sands' aquifer (see Section 4.2.3).

LONDON CLAY FORMATION

This occurs throughout the London and Hampshire basins, except near Dorchester. It is at outcrop throughout a major part of the London Basin. It comprises brown and blue-grey marine clays with a variable mixture of silt and fine sand. In the east of the London area the succession is almost wholly of clays, but to the west and in the Hampshire region several alternations of clays and fine sands can be distinguished.

The London Clay Formation in the London Basin is up to 150 m thick in south Essex and north Kent, thinning westwards to about 90 m at Reading. In the London Basin the youngest part of the London Clay Formation is known as the Claygate Member (formerly the Claygate Beds). This member occurs widely in Surrey, where it comprises orange sands interbedded with pale clays, and is around 15 m thick at Claygate, near Esher. It also occurs as outliers in Essex, where it reaches its maximum thickness of 20 m.

BAGSHOT FORMATION

The strata overlying the London Clay Formation in the London Basin were formerly known as the Lower, Middle and Upper Bagshot beds. The unit previously called the Lower Bagshot Beds is now classified as the Bagshot Formation (Sumbler, 1996), while the other two units have been equated to the Bracklesham Group (see below). The main outcrop of the formation is centred on Bagshot Heath, near Camberley, where it reaches a maximum thickness of about 40 m. Outliers occur in the Newbury area to the west, at Harrow and Hampstead north of London, and also in south Essex, notably at Brentwood and Rayleigh. The formation is dominated by orange/yellow, fine-grained sand, with thin beds of clay.

Bracklesham Group

In the London Basin, the Bracklesham Group comprises the Windlesham Formation and the Camberley Sand Formation, both overlying the Bagshot Formation to the south-west of London. These strata were previously known as the Middle Bagshot Beds and Upper Bagshot Beds respectively. They were provisionally reclassified as the Bracklesham Beds and the Barton Beds respectively because of their probable equivalence to these units in the Hampshire Basin (Sumbler, 1996), but further work has indicated that this terminology is not appropriate (R Ellison, personal communication, 1998). The Camberley Sand Formation consists of fine grained, yellow and white, slightly ferruginous loamy sands. South and east of Newbury, this formation is present as outliers and reaches thicknesses of up to 14 m. Around the Aldershot, Farnborough and Camberley areas, it is up to 70 m thick. The Palaeogene sequences of the London Basin terminate with this formation.

4.2.2.2 *Structural geology*

The London Basin is a major asymmetrical syncline plunging towards the east. Dips on the northern limb of the syncline are uniformly south-eastwards, at angles of less than 1°. The beds of the southern limb dip northwards at steeper angles of up to 3°.

The Palaeogene rocks were subjected to one period of folding after their deposition. This resulted in minor flexures, which can be grouped into dip folds, running roughly north-west to south-east, and strike folds, running north-east to south-west. Although most of the folding is gentle, the crossing of two anticlines tends to produce a dome structure, and the crossing of synclines forms basins. The intersection of dissimilar folds results in an undulating, irregular structural surface.

Two major strike faults are present in south London, both of which downthrow to the north-west. The more northerly, the Wimbledon Fault, affects the London Clay Formation and beds below. The Greenwich Fault brings the Chalk into juxtaposition with the Thanet and Woolwich and Reading formations.

4.2.3 Hydrogeology

4.2.3.1 *Introduction*

The formations within the London Basin that form minor aquifers are described in Table 4.3. The most productive aquifers are the Palaeocene formations, although the younger Bagshot Formation and Camberley Sand Formation are also used for small supplies.

Thanet, Woolwich/Reading and Harwich formations

The Thanet, Woolwich/Reading and Harwich formations are often considered as a single groundwater unit, known as the 'Basal Sands' aquifer, which is in hydraulic continuity with the Chalk. The regional pattern of groundwater flow in this aquifer is from the edge of the basin towards the centre. In the 19th century, water supplies to London were obtained from these beds, but in the early 20th century this practice was abandoned almost entirely in favour of deeper bores into the Chalk. The position of the Palaeogene strata in the London Basin, with their outcrops standing higher than the remainder of the basin, and the fact that they underlay the impermeable London Clay Formation, led to the water in the sands being under artesian conditions. Increasing abstraction gradually dewatered the sands and the wells had to be deepened into the Chalk, although the sands still continued to play a part in distributing water to certain areas of the basin. Over-abstraction from the Chalk continued to dewater the overlying sands, and resulted in the water level in the combined Chalk/Basal Sands aquifer falling below the top of the Chalk on the northern limb and central part of the London Basin. However, since the mid 1960s, declining abstraction has resulted in the water level in the Chalk/Basal Sands aquifer rising at a rate of up to 3 m per year. It is still below the top of the Chalk in a small part of the central London area and on the northern and southern edges of the basin (Environment Agency, 1998), but elsewhere the Palaeogene strata are again water-bearing and mostly fully saturated.

Table 4.3 Formations that act as minor aquifers in the London Basin.

Geological unit	Thickness (m)	Distribution	Lithology	Comments
Camberley Sand Fmn	up to 70	West of London	Well sorted medium grained sand	Formerly Barton Sand or Upper Bagshot Beds
Bagshot Formation	up to 27 in Essex outliers; up to 40 m west of London	Outliers in north London and Essex; Surrey and Berkshire	Mainly fine to medium grained sand with thin beds of clay and clayey silt	Formerly Bagshot Sand or Lower Bagshot Beds
Harwich Formation	up to 12	South-east and north-east London and north Kent	Well sorted, fine to medium sand with flint pebble beds	Includes Blackheath Beds and Oldhaven Beds; may be in hydraulic continuity with Upnor Fmn
Woolwich Formation	10	Mainly central and east London and north Kent	Shelley clay, laminated beds with sand channels 2 to 4 m thick in central London	Formerly Woolwich Beds
Reading Formation	25	Central London and to the west	Highly variable; mottled clay and silt. Fine to medium grained sand in layers and channels may constitute up to 60%	Formerly Reading Beds
Upnor Formation	up to 10	Entire area	Glauconitic sand with thin clay seams	Formerly Woolwich Bottom Beds: may be in hydraulic continuity with Thanet Sand Formation
Thanet Sand Formation	up to 32	East of Harrow to Hounslow	Coarsening upwards silty, fine sand: clay beds at depth in east	Formerly Thanet Sand or Thanet Beds

The proportion of sand in these formations decreases to the west (Figure 4.2). Where clay predominates, although the formations tend to be little-used for water supply, the Basal Sands aquifer provides an aquitard of regional extent, and a useful element of additional drainable storage overlying the Chalk aquifer. Four Thames Region abstraction licences show yields ranging from from 2.95 to 45.5 m^3/d.

Bagshot Formation

The Bagshot Formation has good quality water which is soft but supplies are not large and abstraction is often severely limited by fine silt, easily mobilised from the formation. Measured borehole yields indicate that around 600 m^3/d may be obtained, but supplies of up to 150 m^3/d are more common. Springs occur at the junction with underlying clays. The sands have a moderately low matrix permeability but high effective porosity and storage; consequently boreholes utlising this formation tend to have reliable but low to medium yields. The Environment Agency (Thames Region) abstraction register shows 37 licences with abstractions ranging from 1.82 to 655 m^3/d, with an arithmetic mean of 76.7 m^3/d. The high volume of storage in this formation combined with a thickness of around 30 m or more also means that abstraction effects on surface water flow are minimal. This provides scope in the London Basin for greater abstraction from this under-utilised aquifer. To provide continuous yields in excess of 100 m^3/d would, however, require boreholes penetrating the full saturated thickness and careful design to avoid problems of siltation.

Camberley Sand Formation

Small supplies only are obtained from the Camberley Sand Formation; the water is usually soft but may be ferruginous. Measured borehole yields indicate that 100 m^3/d may be obtained, but supplies of up to 50 m^3/d are more common. Springs occur at the junction with the Windlesham Formation. Yields may be gauged from the six abstraction licences for this Group (Environment Agency, Thames Region) which range from 3.41 to 136.4 m^3/d for the Bracklesham Beds and from 8.82 to 13.1 m^3/d for the Barton Beds. As a groundwater resource, the Camberley Sand Formation is considered secondary to the Bagshot Formation in the London Basin.

4.2.3.2 *Previous studies*

The Hydrogeology of the London Basin (Water Resources Board, 1972) was concerned with assessing the feasibility of artificially recharging the Chalk and Palaeogene sands beneath the London Clay Formation. The study covered the central part of the London Basin between Windsor and Gravesend, and included detailed studies of the permeability of the formations between the London Clay Formation and the Chalk, as well as hydrogeological interactions.

4.2.3.3 *Core data*

It has long been recognised that the unconsolidated nature of most of the Palaeogene minor aquifers makes it difficult to measure the permeability of core samples directly. The hydraulic conductivity results for the Palaeogene deposits of both the London and Hampshire basins have been described in Section 4.1.4.1; these largely comprise estimates by the Water Resources Board (1972) of hydraulic conductivity for the Thanet, Reading and Woolwich and Harwich formations based on grain size distribution. The results for the London Basin are summarised as follows.

Thanet Formation

This is composed of uniform fine sands, with a median grain size varying between 0.06 and 0.10 mm. The hydraulic conductivity is between 1.39 and 3.89 m/d, with an average of 2.5 m/d (Water Resources Board, 1972).

Lambeth Group

The sands of the Reading and Woolwich formations are less uniform than those of the Thanet Formation. They are predominantly medium sands but include some fine sands. The average median grain size is about 0.3 mm, with a range from 0.095 to 0.5 mm (except where gravel occurs). The variation of the hydraulic conductivity at any one locality is likely to be between 2 and 60 m/d, with a tendency to increase towards the top of the deposit. A representative average value is about 20 m/d. Gravel layers of the Upnor Formation may have a hydraulic conductivity as high as 200 m/d, but these layers are uncommon, and their thickness is too limited to have much influence on the transmissivity of the formation as a whole.

Harwich Formation

The pebbly-sand facies of the Harwich Formation was only sampled in east and south-east London; no information is available for the large area north-east of London where the formation also occurs. The sand fraction was well sorted, with the 50% grain size varying between 0.1 and 0.425 mm, the average being 0.145 mm. The hydraulic conductivity of the sand matrix ranges from less than 2 to 70 m/d, with an average of 10 m/d. Where the deposit contains more than 65 % gravel, the average hydraulic conductivity is likely to be between 10 and 15 m/d.

The estimates of hydraulic conductivity described above were derived from a laboratory test, and to be related to field values the stress imposed by the overlying strata must be taken into account.

London Clay Formation

The London Clay Formation is an extensively fissured, over-consolidated clay. Measurements of hydraulic conductivity (Water Resources Board, 1972) indicated that the clay fraction of the formation has an average hydraulic conductivity of 10^{-3} m/d, but the value for fissured clay near the surface may be 10^{-2} m/d. Values may be even higher in exceptional circumstances, that is, where the fissuring is particularly prevalent.

4.2.3.4 *Pumping test results*

These are summarised for all Palaeogene sites in the London Basin in Table 4.4 and Figures 4.5 and 4.6.

There were 11 values of transmissivity, ranging from 10 to 522 m^2/d, with a geometric mean of 48.6 m^2/d, and a median of 38 m^2/d. Six values of storage coefficient ranged from 0.0001 to 0.06. Thirty five values of specific capacity were available, ranging from 2.4 $m^3/d/m$ to 469 $m^3/d/m$. Both transmissivity and specific capacity values have an approximately log-normal distribution.

4.2.3.5 *Controls on permeability and transmissivity*

The major control on permeability and transmissivity is lithological variation. As clayey beds overlie many of the formations, recharge may be limited and this, together with lateral changes in facies, is thought to explain why well yields may decline with time.

Structure does not exert a major control on aquifer properties of the Palaeogene beds in the London Basin.

4.2.3.6 *Areal distribution of aquifer parameters*

The aquifer properties of the Palaeogene minor aquifers are controlled by the proportion of sand compared to clay. The

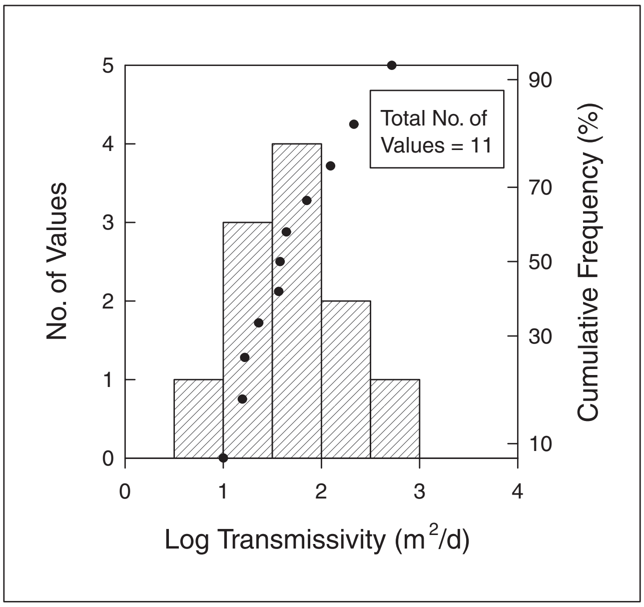


Figure 4.5 Distribution of Palaeogene strata transmissivity results from pumping tests in the London Basin.

Table 4.4 Summary of aquifer properties data for the Palaeogene of the London Basin**.**

Palaeogene of the London Basin		
Total number of records	38	—
Number of transmissivity records	11	—
Minimum/maximum transmissivity value (m^2/d)	10.0	522
Arithmetic/geometric mean of transmissivity (m^2/d)	101	48.6
Median/interquartile range of transmissivity (m^2/d)	38.0	107
25/75 percentile of transmissivity (m^2/d)	17.0	124
Number of storage coefficient records	6	—
Minimum/maximum storage coefficient value (m^2/d)	0.0001	0.06
Number of specific capacity records	35	—
Minimum/maximum specific capacity ($m^3/d/m$)	2.38	469
Arithmetic/geometric mean of specific capacity ($m^3/d/m$)	58.9	24.9
Median/interquartile range of specific capacity ($m^3/d/m$)	26.5	38.0
25/75 percentile of specific capacity ($m^3/d/m$)	8.57	46.6

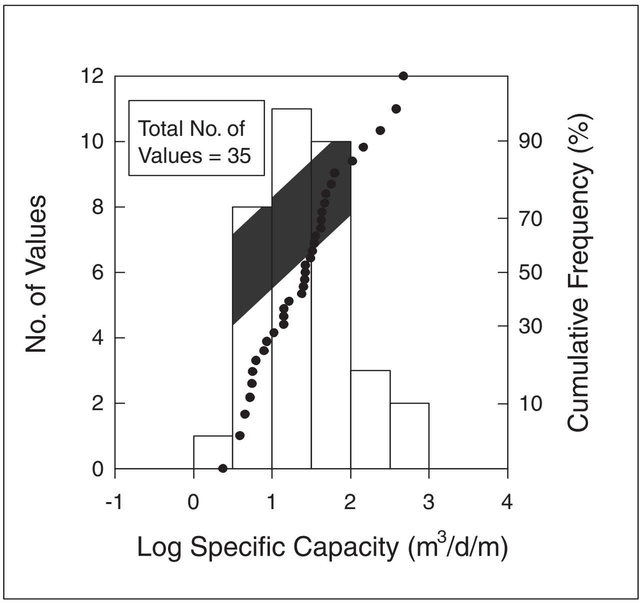


Figure 4.6 Distribution of Palaeogene strata specific capacity results from pumping tests in the London Basin.

Water Resources Board (1972) examined this factor for the Basal Sands aquifer. It was found that the sand proportion gradually increases towards the east until in north Kent and south-east Essex the formations are predominantly composed of sand (Figures 4.7 and 4.8). As the sands are in hydraulic continuity with the underlying Chalk, they are usually treated as a single aquifer.

4.3 THE HAMPSHIRE BASIN

4.3.1 Introduction

The Palaeogene rocks of the Hampshire Basin are separated from those of the London Basin by the anticline of the Weald and by the Chalk of the Hampshire Downs. The complete succession from the base of the Reading Formation to the top of the Bouldnor Formation would span around 700 m. Although nowhere in the region is the complete succession present, at Whitecliff Bay on the Isle of Wight, a near-complete sequence over 600 m thick is visible, extending from the base of the Reading Formation to the Bembridge Marls Member of the Bouldnor Formation.

As in the London Basin, the Palaeogene outcrops have a subdued topography compared with the adjacent Chalk downs. Minor topographical features occur.

4.3.2 Geology and stratigraphy

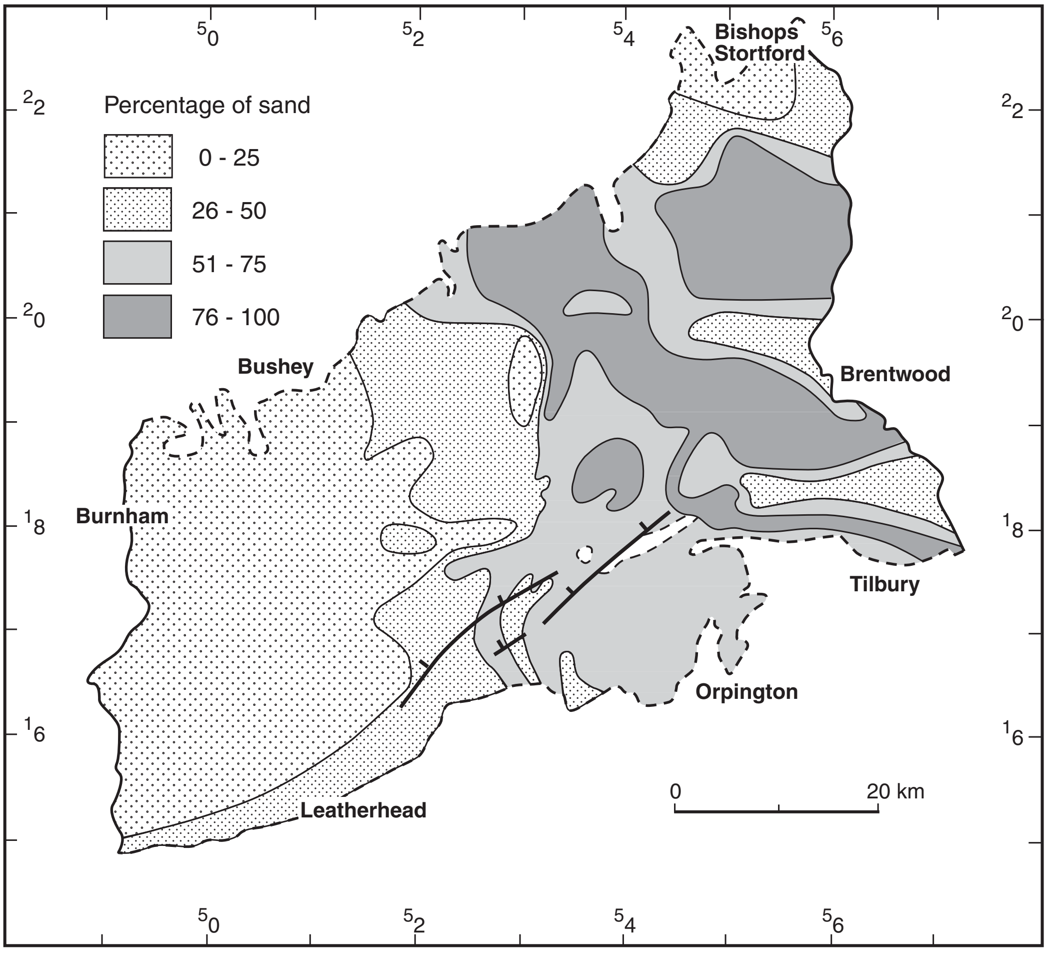
The geology is described below and the relationships between strata are illustrated in Figure 4.3.

4.3.2.1 *Lithology and stratigraphy*

Reading and Woolwich formations

The Reading and Woolwich formations are of approximately lateral equivalence, and are present throughout the

Figure 4.7 Percentage of sand in the Palaeogene strata of the London Basin (adapted from Water Resources Board, 1972).



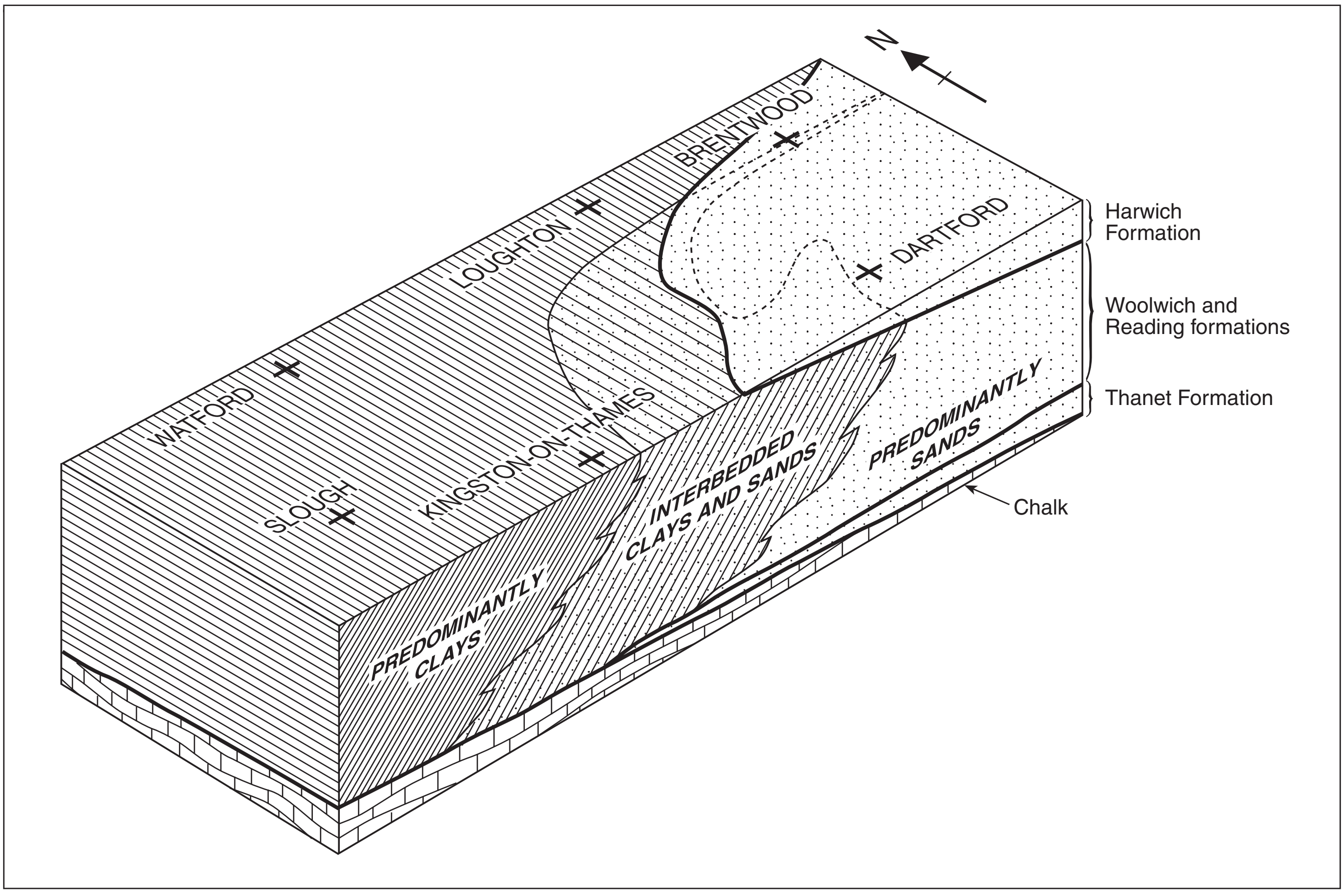


Figure 4.8 Relationship between the principal lithologies of the Palaeogene strata of the London Basin (adapted from Water Resources Board, 1972).

London and Hampshire basins. In the Hampshire Basin, the Reading Formation has a thickness of around 20 m and is generally sandier at the northern end of the basin, thickening towards the south.

London Clay Formation

This occurs throughout the London and Hampshire basins, except near Dorchester. It comprises brown and blue-grey marine clays with a variable mixture of silt and fine sand. Although in the east of the London area the succession is almost wholly of clays, in the Hampshire region several alternations of clays and fine sands can be distinguished.

In the Hampshire Basin, the thickness of the London Clay Formation varies from 30 m or less in the west to over 140 m in the east. Sandier divisions known as the Whitecliff Sand, Durley Sand, Nursling Sand and Portsmouth Sand occur within the formation. All of these four named sands were included partly or wholly in the Bagshot Beds of older classifications (Edwards and Freshney, 1987). Since these occur as lenticular bodies channelled into the underlying strata, they are discontinuous. The Whitecliff Sand occurs at the top of the London Clay Formation and has a thickness of 10 to 25 m, thinning from west to east. The Durley Sand is only present around that locality. The Nursling Sand has an extensive outcrop in the north and north-west of the basin and is up to 30 m thick. The Portsmouth Sand outcrops in the eastern part of the basin and is around 10 m thick.

Bracklesham Group/Bournemouth Group

In the eastern part of the Hampshire Basin, the London Clay Formation is overlain by the thick marine sequence of the Bracklesham Group. This corresponds approximately to the Middle and Upper Bagshot Sands and Bracklesham Beds of earlier classifications (Edwards and Freshney, 1987). The Bracklesham Group is a series of clayey sands which are typically more coarse-grained than the London Clay Formation and is notably glauconitic. It contains four major sedimentary cycles, named in ascending order the Wittering Formation (laminated and glauconitic sandy clays), Earnley Sand Formation (bioturbated sandy marine clays), Marsh Farm Formation (laminated clays) and Selsey Sand Formation (fine-grained sand).

The Bracklesham Group outcrops in an arc from Christchurch in the west, through Ringwood and along the coast from Southampton to Portsmouth, and also on Selsey Bill. A further discontinuous outcrop, mostly of the Wittering Formation, to the north-east, between Romsey and Waterlooville, is separated from the rest of the group by an area of London Clay Formation and Chalk, which crops out in an anticlinal inlier. A narrow strip of the Bracklesham Group also outcrops from east to west across the Isle of Wight. The group thins from east to west and from south to north, reaching a thickness of up to 180 m on Selsey Bill and the Isle of Wight.

In the western half of the Hampshire Basin the Bracklesham Group passes progressively westwards into deposits of a continental type. In Dorset, lateral equivalents of the Bracklesham Group are to be sought in the pale sands, pipeclay and lignitic clays of the Branksome Sand Formation, and possibly the underlying Poole Formation. These, together with the overlying Boscombe Sand Formation, form the Bournemouth Group.

Barton Group

In the Hampshire Basin, the Bracklesham Group is overlain by the new sedimentary cycle of the Barton Group. The Barton Group coarsens upwards from the predominantly argillaceous Barton Clay Formation, through the clayey fine-grained sands of the Chama Sand Formation to the relatively clay-free sands of the Becton Sand Formation. To the west of Christchurch, the Barton Group passes into the Boscombe Sand Formation.

The Barton Group is only present to the west of Southampton Water and on the Isle of Wight. In the New Forest area, the thickness varies from 50 m to 80 m, thinning from south to north. It is at outcrop in the New Forest and becomes overlain by the Headon Hill Formation to the south, except for an inlier around Lymington. On the Isle of Wight it is up to around 100 m thick, again thinning to the north and largely overlain by the Headon Hill Formation.

Solent Group

HEADON HILL FORMATION

This formation comprises the units formerly known as the Osborne and Headon beds, and is mainly clay with beds of limestone. On the Isle of Wight, it has a thickness of 70 m in the west and 100 m in the east.

BEMBRIDGE LIMESTONE FORMATION

This massive pale limestone with intercalated green clay is only present on the Isle of Wight and has a thickness of around 5 m.

BOULDNOR FORMATION

The Bouldnor Formation is present on the Isle of Wight and in a small area round Lymington. It comprises grey clays with sand followed by coloured clays with occasional beds of loam, sand and shales and some bands of limestone. The formation is present over the greater part of the northern half of the Isle of Wight, and is up to 75 m thick. On the mainland its maximum thickness is 70 m.

4.3.3 Hydrogeology

4.3.3.1 *Introduction*

The Palaeogene formations that form minor aquifers are described below and in Table 4.5.

Reading Formation

In the northern part of the Hampshire Basin, sandy strata are generally present in the Reading Formation. North of Southampton, yields can be up to 200 m^3/d from boreholes, although this may be partly due to upward recharge to the basal sands from the underlying Chalk. A more usual yield is less than 100 m^3/d, and boreholes may be dry where sand members are thin or absent. The sandy nature of the basal members is important in relation to the underlying Chalk because it is thought to lead to enhanced development of dolines and other solution features. The latter are especially common on the northern flanks of the Portsdown Anticline between Soberton and Walderton.

In the western, southern and eastern parts of the basin, the formation is predominantly clay and is unproductive for water supply.

London Clay Formation

Due to its clayey nature, the majority of the London Clay Formation is of little significance as an aquifer. However, in the higher part of the formation, lenticular beds of fine to medium grained sands, including the Nursling, Portsmouth and Whitecliff sands, may constitute useful aquifers. The most important of these is at the top of the formation where boreholes of 200 mm diameter or less may yield up to 500 m^3/d from the Whitecliff Sand (Edwards and Freshney, 1987). Supplies are best where the width of outcrop and underground structure are favourable for collection and storage of water, as at Gosport; otherwise supplies are small. Water quality is variable, sometimes being high in iron, and salt water may be obtained in the coastal belt, as at the southern end of Hayling Island. Numerous springs occur at the junction with underlying clay fractions.

Test drilling in the Fawley area indicated that the Whitecliff Sand did not prove to be as productive an aquifer as had been expected (Lowings and Giles, 1987). Furthermore, some boreholes penetrating the London Clay Formation did not intercept the Whitecliff Sand, due to its lateral discontinuity.

Bracklesham Group

Rapid lateral and vertical variations in the sand and clay content of the formations of the Bracklesham Group have a commensurate effect on aquifer properties. In the areas to the north and west of the New Forest, and between Southampton and Gosport, sandy beds are fairly well developed, and boreholes of up to 200 mm diameter may yield up to 200 m^3/d; those over 400 mm diameter have given more than 1800 m^3/d from the sandier strata. However, the water may be ferruginous.

In the Fawley area, it has been suggested that the formations within the Bracklesham Group, and the Whitecliff Sand, may act together as a single aquifer (Lowings and Giles, 1987). Hydraulic continuity is likely to exist only sporadically between the formations due to lateral and vertical variations in sand and clay content. The Bracklesham Group at this location is mostly represented by the Marsh Farm Formation which is clay dominant. However, the lower part of the Wittering Formation, which in that area is sand dominant, is also present.

On the Isle of Wight, small springs issue from the formations of the Bracklesham Group. However, boreholes into the formations are not common.

Bournemouth Group

In the Bournemouth area, the Bournemouth Group (formerly the Bagshot and Bracklesham Beds), comprising the Poole, Branksome Sand and Boscome Sand formations, is the principal water-bearing formation of the district. Water flows in small quantities from the base of the Poole Formation, and elsewhere at various levels due to clayey beds in the sands. However, most groundwater percolates to the base of the beds and emerges in the bottom of river valleys or at the coast.

The Boscome Sand Formation, formerly the Barton Sand, is present in the west of the basin. Springs issue from the formation, but it is rarely used for water supply.

Barton Group

On the mainland, groundwater level data indicate that groundwater flow is predominantly from the north towards the sea. On both the mainland and the Isle of Wight, the aquifer becomes confined by the overlying Headon Formation.

While more arenaceous horizons within the Barton Clay and Chama Sand may yield small supplies, the Becton Sand forms the most useful and reliable aquifer. In the New Forest area, yields are best in the south of the area where

Table 4.5 Formations that act as minor aquifers in the Hampshire Basin.

Geological unit	Thickness (m)	Distribution	Lithology	Comments
Headon Hill Formation	66 to 100	New Forest; Isle of Wight	Highly variable: sands, silts, clays, thin lignites, limestones (Bembridge Lst). Locally indurated sands	Includes strata formerly known as Osborne and Headon beds
Becton Sand Formation	10 to 45	New Forest; Isle of Wight	Well sorted, fine-grained sand; locally thick clays in middle part	Formerly mapped as Barton Sand
Chama Sand Formation	7 to 15	New Forest; Isle of Wight	Clayey, glauconitic, fine-grained sand	Formerly mapped as Barton Sand
Boscombe Sand Formation	up to 20	Bournemouth–Ringwood area	Well sorted, fine-grained sand	Passes in Barton Clay east of Christchurch
Selsey Sand Formation	average 30	Eastern part of the basin	Silty sand and sandy, clayey silt	Part of the Bracklesham Group
Earnley Sand Formation	up to 25	Eastern part of the basin	Mainly glauconitic, silty sand	Part of the Bracklesham Group
Branksome Sand	70	Bournemouth–Ringwood area	Fine to very coarse-grained sand with thin lenticular clays in cyclical sequences	Formerly part of the 'Bournemouth Freshwater and Marine Beds'
Poole Formation	30 to 160	Between Poole and Wareham	Medium to coarse-grained sand, alternating with brown, red-brown and pale grey clays	Formerly known as Lower Bagshot Beds
London Clay Fmn:	70 to 90		Lenticular, variable silty, fine- to coarse-grained sands	London Clay thins to 20 m in Dorset
Nursling Sand	up to 4	W of Southampton		
Portsmouth Sand	up to 8	Most of basin		
Whitecliff Sand	up to 15	Most of basin		
Reading Formation	average 28	Entire basin	Highly variable. Mostly brightly mottled clays in Isle of Wight. In north of basin, almost entirely sand with lenticular gravel and ironstone bands in places	

300 mm diameter boreholes into the Becton Sand yield up to 600 m^3/d. Northwards, yields are poorer, rarely exceeding 200 m^3/d. Where the Becton Sand is absent, the Barton Group is poorly productive.

Despite the extensive outcrop in the New Forest area, the aquifer is currently little used by private abstractors because of the difficulty of constructing boreholes that are stable and do not draw in fines. However, due to increasing water demands more users are considering the aquifer potential of the Barton Group.

On the Isle of Wight, the beds give rise to small springs throughout their extent. Boreholes may be artesian where the group is confined by the Headon Formation. A number of boreholes were drilled into the Becton Sand at the turn of the century in the Newport and Cowes area, to depths of over 200 m. Most are now abandoned or disused, due to sand ingress, falling yield, or unacceptable groundwater quality. Yields of up to 1000 m^3/d were obtained, but boreholes were liable to choke with silt. The water is soft and liable to be ferruginous, with iron concentrations of 1 to 2 mg/l.

Headon Hill Formation

In the New Forest, this formation dominantly acts as an aquiclude over the underlying Barton Group. However, where sandy strata are developed, yields sufficient for domestic or small agricultural requirements have been obtained from shallow wells. The formation has also been used for water supply in the north of the Isle of Wight.

Bembridge Limestone Formation

The Bembridge Limestone yields small supplies, but the water is ferruginous and unpalatable.

Bouldnor Formation

On the Isle of Wight, domestic supplies have been obtained from boreholes up to 25 m deep from the sandy beds of the Hamstead Member but the formation is otherwise poorly productive.

4.3.3.2 *Aquifer properties*

In the Fawley area it has been assumed that the Bracklesham Group and Whitecliff Sands (within the London Clay Formation) act as a single aquifer; they have an aquifer transmissivity of 50 to 100 m^2/d and confined storage coefficients of between 0.01 and 0.1% (Lowings and Giles, 1987). In the aquifer outcrop area, an unconfined storage coefficient of about 2% is employed (Environment Agency, personal communication, 1997). Test boreholes in the Fawley area indicated that the best supplies were obtained from the

Wittering Formation of the Bracklesham Group, rather than the Whitecliff Sand of the London Clay, as had previously been anticipated.

For the Poole Formation, the Environment Agency employ an estimated regional transmissivity figure of around 20 m^2/d, with a storage coefficient of 1% (Environment Agency, personal communication, 1997).

Due to the stratigraphic and lithological complexity of the Barton Group, transmissivity and storage coefficient values may well be very variable and in the absence of an adequate number of pumping test results, reasonable, but assumed, regional values are often used for such purposes as estimating abstraction effects when determining licence applications. Estimates of transmissivity for the Barton Group (Becton Sand) are of the order of 50 to 100 m^2/d; estimates of storage coefficient are 0.02% where the aquifer is confined and 5% where it is unconfined (Environment Agency, personal communication, 1997).

4.3.3.3 *Core data*

Barton (1989) carried out laboratory permeability tests on the Becton Sand from the Isle of Wight. Values of porosity ranged from 28.7% to 39.2%; excluding two particularly clay-rich samples, the range was from 34.7% to 39.2%. These values are consistent with the sands being of a dense state of compaction. Values of permeability ranged from 8×10^{-3} to 15 m/d, with an average value of 1.7 m/d.

4.3.3.4 *Pumping test results*

Pumping test results are summarised for all Palaeogene sites in the Hampshire Basin in Table 4.6. The distribution of specific capacity values is shown in Figure 4.9; there were insufficient transmissivity or storage coefficient values to plot their distribution. Eight values of transmissivity were obtained, ranging from 1.1 to 1600 m^2/d. Six values of storage coefficient ranged from 0.00002 to 0.05. There were 42 values of specific capacity, ranging from 3.6 to 4000 m^3/d/m, with an interquartile range of 21 to 103 m^3/d/m, and a geometric mean of 44.5 m^3/d/m. The transmissivity and storage coefficient values agree with the estimates given by other workers (see above).

4.3.3.5 *Controls on permeability and transmissivity*

As for the London Basin, the major control on permeability and transmissivity in the Hampshire Basin is lithological variation. As clayey beds overlie many of the formations, recharge may be limited, while lateral facies changes may cause the yields of wells to decline with time.

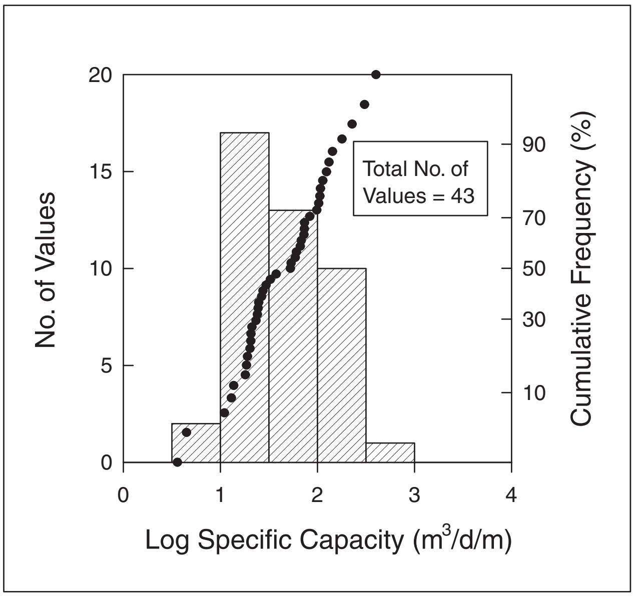


Figure 4.9 Distribution of Palaeogene strata specific capacity results from pumping tests in the Hampshire Basin.

4.3.3.6 *Effect of structures*

Structural controls on the permeability of the Palaeogene minor aquifers have not been reported. Small faults may result in barrier effects.

4.4 COMPARISON OF AQUIFER PROPERTIES BETWEEN LONDON AND HAMPSHIRE BASINS

With such an inadequate array of data, there is only very limited opportunity to compare the aquifer properties of equivalent formations across the London and Hampshire basins. Figures 4.10a and b show specific capacities for the Bagshot Formation of the London Basin, and the combined Bracklesham Group (eastern Hampshire Basin) and Poole Formation (western Hampshire Basin). Bearing in mind the risk of over-interpretation of specific capacity values, it would

Table 4.6 Summary of aquifer properties data for the Palaeogene of the Hampshire Basin.

Palaeogene of the Hampshire Basin		
Total number of records	46	—
Number of transmissivity records	8	—
Minimum/maximum transmissivity value (m^2/d)	1.05	1600
Arithmetic/geometric mean of transmissivity (m^2/d)	429	72.2
Median/interquartile range of transmissivity (m^2/d)	72.5	756
25/75 percentile of transmissivity (m^2/d)	17.8	774
Number of storage coefficient records	6	—
Minimum/maximum storage coefficient value	0.00002	0.05
Number of specific capacity records	43	—
Minimum/maximum specific capacity (m^3/d/m)	3.61	400
Arithmetic/geometric mean of specific capacity (m^3/d/m)	72.9	44.5
Median/interquartile range of specific capacity (m^3/d/m)	52.7	82.6
25/75 percentile of specific capacity (m^3/d/m)	20.7	103

appear that the range of the Bagshot Formation is slightly less than its Bracklesham Group lateral equivalent in the Hampshire Basin, but the mean and median values of specific capacity are typically higher (geometric means of 50.4 and 36.7 respectively). This may indicate a greater homogeneity in the component sandy members of the Bagshot Formation of the London Basin.

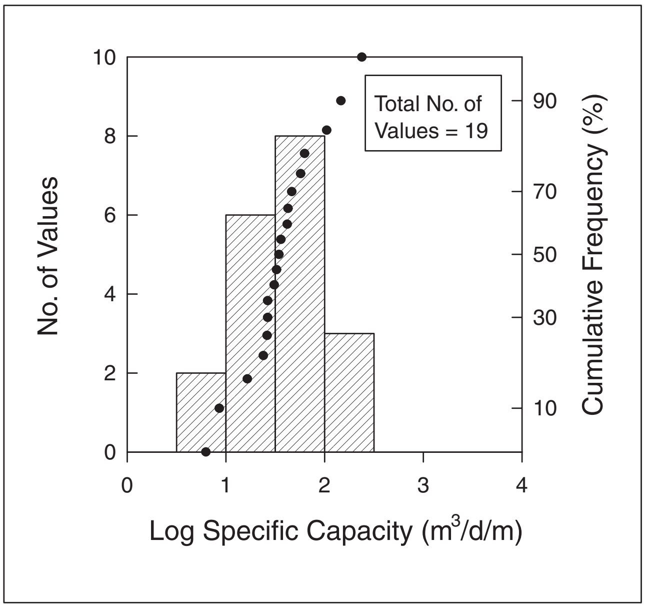


Figure 4.10a Specific capacity results from pumping tests in the Bagshot Formation of the London Basin.

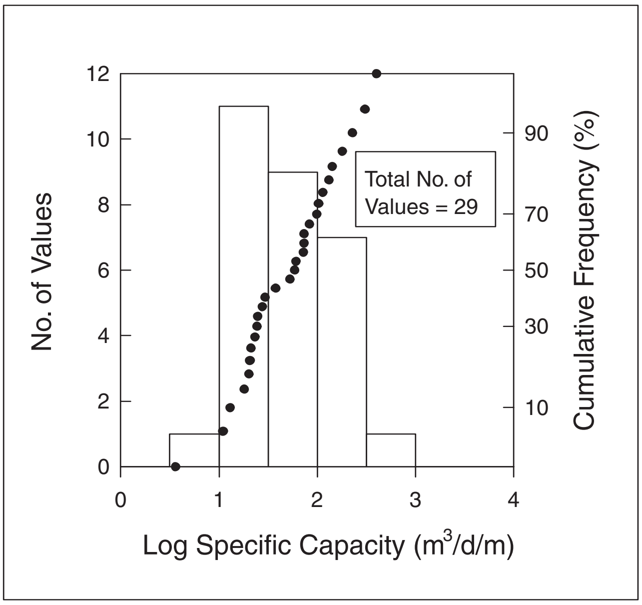


Figure 4.10b Specific capacity results from pumping tests in the Bracklesham Group/Poole Formation of the Hampshire Basin.

An inspection of specific capacities for the combined Bracklesham Group and Poole Formation shows that despite an estimated regional transmissivity of only about 20 m^2/d (see previous section), this group provides a number of boreholes with specific capacities in excess of 100 m^3/d/m. This points to locally higher transmissivities in the sand formations within the group.

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5 Cretaceous minor aquifers

5.1 INTRODUCTION

This chapter describes a number of minor aquifers of Early Cretaceous/Late Jurassic age. These include the Upper Greensand Formation of the Weald and southern England, and the Lower Cretaceous/Upper Jurassic sequences in three separate areas: the Weald, northern East Anglia, and Lincolnshire. To some extent this chapter complements the extensive treatment of the Chalk and Lower Greensand Group in Allen et al. (1997). However, in Allen et al., (1997) the Upper Greensand was only discussed as an adjunct to the Chalk, with which it is frequently, but not invariably, in hydraulic continuity. In some areas, the Upper Greensand is an aquifer in its own right, and that situation is covered in this chapter. Allen et al. (1997) also described the Woburn Sands Formation and the Lower Greensand Group of the Weald as they are major aquifers, but other aquifers of Aptian age were not covered.

Lower Cretaceous deposits are found in southern England in the Weald area and in an arc from Devon through western Norfolk to South Yorkshire. The distribution of sediments is due to the occurrence of a very late Jurassic eustatic fall in sea level, accompanied by a sudden increase in tectonic activity (late Cimmerian movements), which resulted in the majority of England and Wales becoming land. Thus sedimentation was limited to two main areas, separated by the East Anglian Massif (see Figure 5.1). In the north, the inundation stretched from north Norfolk to Yorkshire, and in the south sedimentation occurred across the Wessex Basin and adjacent areas. These areas are dealt with individually below. The contemporaneous Woburn Sands Formation was deposited along the 'Bedfordshire Straits' (see Allen et al., 1997). By late Albian times, the Market Weighton High and the East Anglian Massif had been submerged, and the shoreline was moving westwards.

The 'Lower Cretaceous' sequence contains several minor aquifers. The Spilsby Sandstone in Lincolnshire was for many years, considered to be Cretaceous in age, but evidence from ammonites has actually shown it to be partially Jurassic (Kent, 1980). It is therefore technically incorrect to call the formating simply 'Lower Cretaceous Sands'; they are more correctly referred to as 'Upper Jurassic–Lower Cretaceous deposits'. However, it is useful shorthand and, for the purpose of this report, the sediments are referred to as Lower Cretaceous sands. Above these are various minor sandstone aquifers, intercalated with argillaceous deposits (see Table 5.1). The youngest Lower Cretaceous aquifer is the Upper Greensand Formation in the Wealden and Vectian Basins.

5.1.1 General geology and stratigraphy

The geology and stratigraphy of the different formations is only dealt with briefly here; it is discussed in more detail in the sections on the individual aquifers.

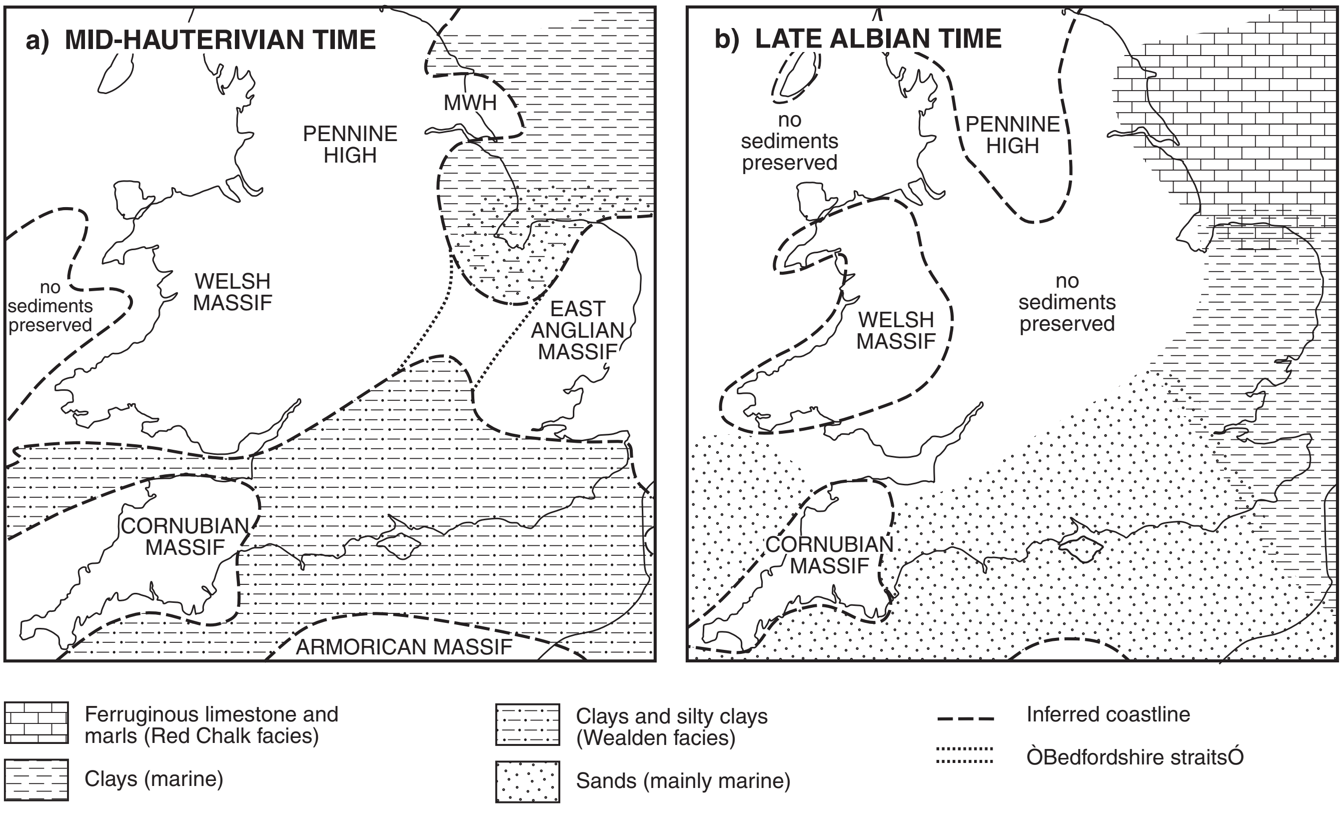
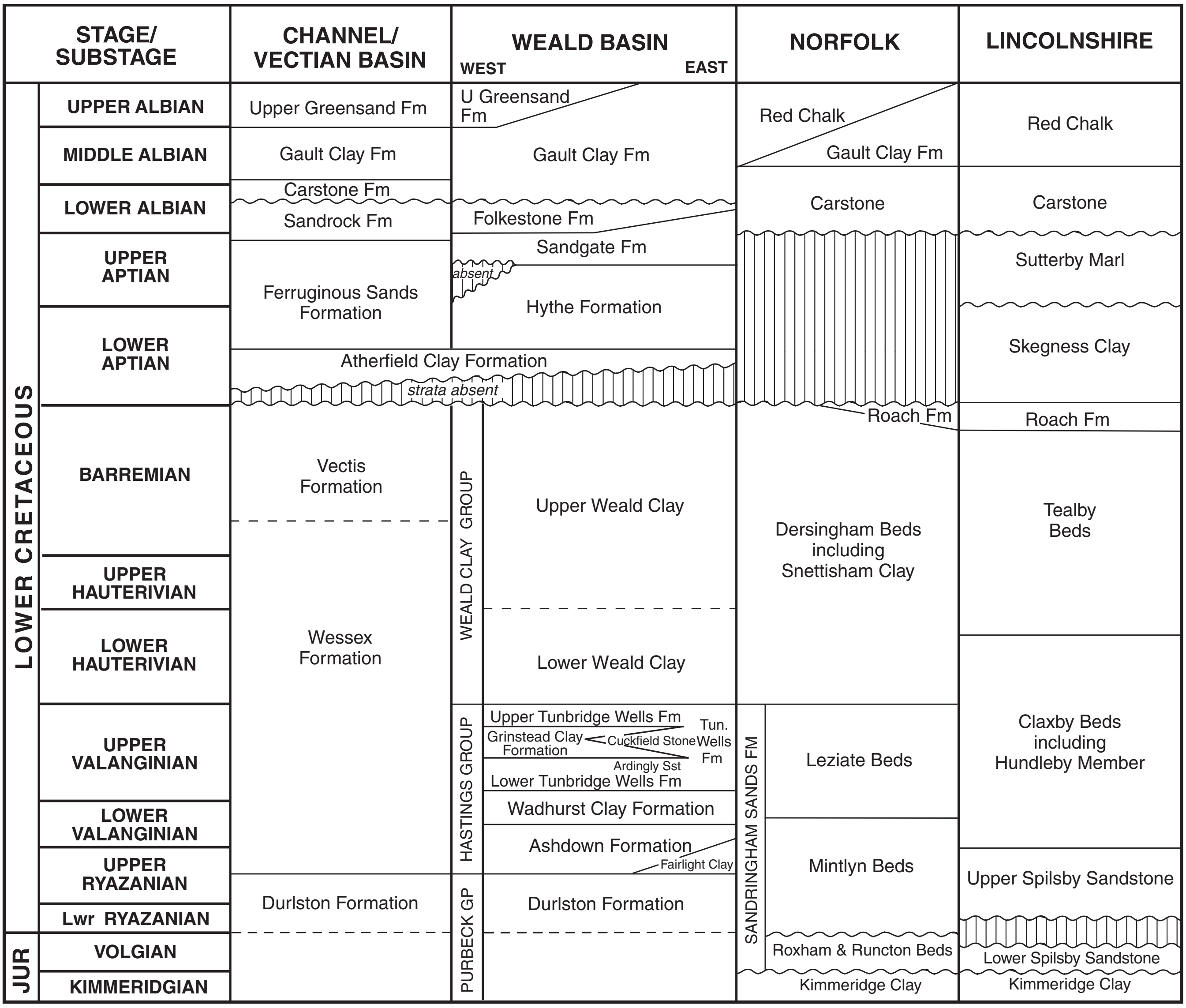


Figure 5.1 Early Cretaceous palaeogeography and facies during mid-Hauterivian and late Albian times (from Rawson, 1992).

Table 5.1 Stratigraphy and relationships of the Lower Cretaceous/uppermost Jurassic rocks of southern and eastern England (adapted from Rawson, 1992).



	STAGE/ SUBSTAGE	CHANNEL/ VECTIAN BASIN	WEALD BASIN (WEST – EAST)		NORFOLK		LINCOLNSHIRE
LOWER CRETACEOUS	UPPER ALBIAN	Upper Greensand Fm		U Greensand Fm		Red Chalk	Red Chalk
	MIDDLE ALBIAN	Gault Clay Fm		Gault Clay Fm		Gault Clay Fm	
	LOWER ALBIAN	Carstone Fm Sandrock Fm		Folkestone Fm		Carstone	Carstone
	UPPER APTIAN	Ferruginous Sands Formation		Sandgate Fm absent Hythe Formation			Sutterby Marl
	LOWER APTIAN	Atherfield Clay Formation strata absent		Atherfield Clay Formation strata absent			Skegness Clay
	BARREMIAN	Vectis Formation	WEALD CLAY GROUP	Upper Weald Clay		Roach Fm Dersingham Beds including Snettisham Clay	Roach Fm Tealby Beds
	UPPER HAUTERIVIAN	Wessex Formation					
	LOWER HAUTERIVIAN			Lower Weald Clay			Claxby Beds including Hundleby Member
	UPPER VALANGINIAN		HASTINGS GROUP	Upper Tunbridge Wells Fm Grinstead Clay Formation Cuckfield Stone Ardingly Sst Tun. Wells Fm Lower Tunbridge Wells Fm	SANDRINGHAM SANDS FM	Leziate Beds	
	LOWER VALANGINIAN			Wadhurst Clay Formation		Mintlyn Beds	
	UPPER RYAZANIAN			Ashdown Formation Fairlight Clay			Upper Spilsby Sandstone
	Lwr RYAZANIAN	Durlston Formation	PURBECK GP	Durlston Formation			
JUR	VOLGIAN					Roxham & Runcton Beds	Lower Spilsby Sandstone
	KIMMERIDGIAN					Kimmeridge Clay	Kimmeridge Clay

5.1.1.1 *Extent of aquifer groups*

Lower Cretaceous/Upper Jurassic sediments described here comprise minor aquifers over parts of the Weald, northern East Anglia, and Lincolnshire. Their outcrop across the Weald and southern England is shown in Figure 5.2. Further north, they outcrop as a long, thin strip, from south of the Humber in the north to approximately Ely in the south, with the main areas of interest being in Norfolk and Lincolnshire (see Figure 5.3). The lower Cretaceous outcrop continues south-west of Ely, as it becomes the Woburn Sands aquifer (see Allen et al., 1997). The deposits are overlain by the Gault Clay Formation and/or Chalk to the east, and underlain by the Kimmeridge Clay.

5.1.1.2 *Stratigraphy and lithology*

In the Wealden area, the general sequence is one of non-marine sediments, followed by the marine Lower Greensand Group, and Gault Clay and Upper Greensand formations (Rawson, 1992). Sedimentation in this area may have been affected by contemporaneous faulting, especially along the southern margin of the East Anglian Massif (Rawson, 1992).

North of the East Anglian Massif, the East Midlands Shelf was bounded to the north and east by active fault systems. The northern part of the shelf was emergent and formed the Market Weighton High. Over the southern part of the shelf, shallow marine sediments accumulated in a depositional area known as the Spilsby Basin (Rawson, 1992). Facies and faunal distributions indicate a nearshore environment in north Norfolk and south Humberside, with a broad offshore environment in between. Phosphatic nodule beds in the Spilsby Sandstones and Norfolk equivalents suggest there may have been widespread pauses in deposition (Rawson, 1992). An important early Albian transgression is marked by the presence of the Carstone Formation, and this represents a more widespread phase of sedimentation.

The differing stratigraphic names used in southern England, north Norfolk, and Lincolnshire (see Table 5.1) are broadly equivalent. The change in terminology between Norfolk and Lincolnshire may be, in part, due to facies change, but is primarily due to different workers erecting different stratigraphies on either side of The Wash (B Moorlock, personal communication).

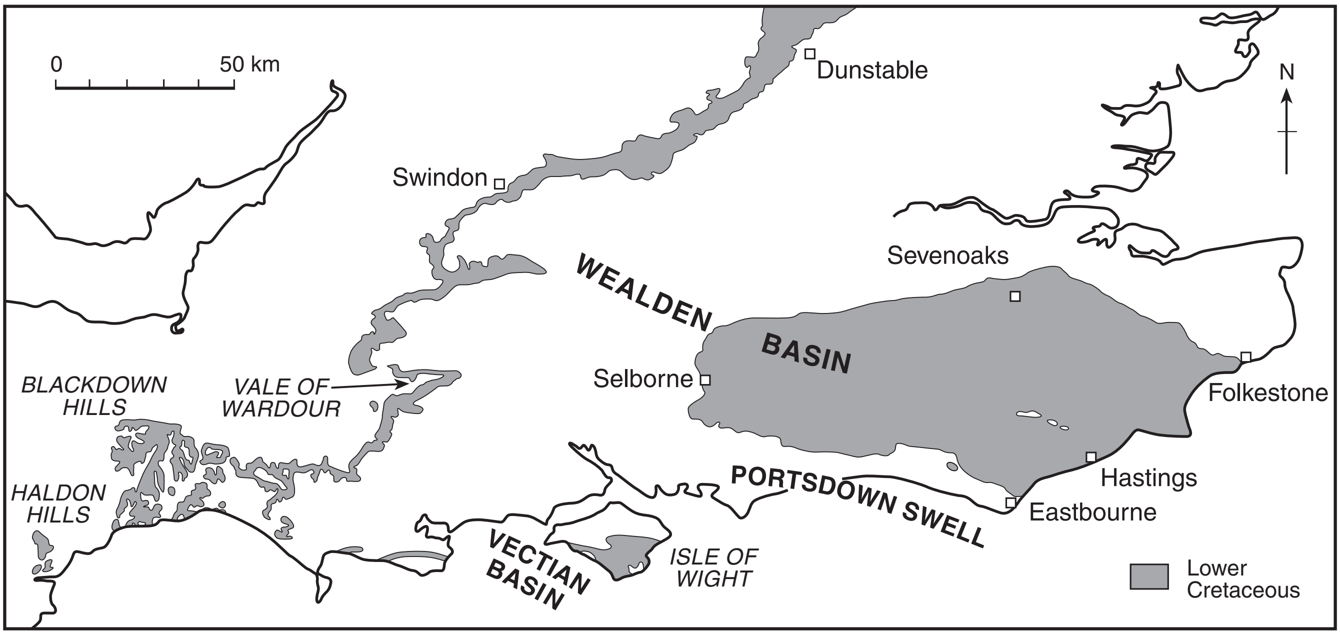


Figure 5.2 Outcrop of Lower Cretaceous/uppermost Jurassic rocks in the Weald and southern England (from Rawson, 1992).

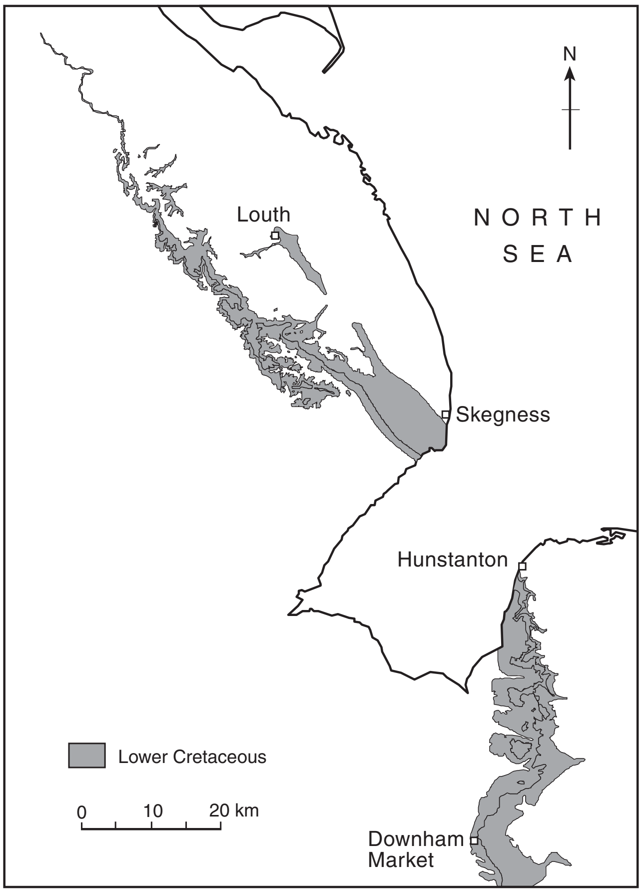


Figure 5.3 Outcrop of Lower Cretaceous/uppermost Jurassic rocks in eastern England.

5.1.1.3 *Igneous activity*

There are no known volcanic rocks within the Sandringham Sands, Spilsby Sandstone, Dersingham Beds or the Roach Formation, or within the Wealden facies.

5.1.2 General hydrogeology

The Lower Cretaceous/Upper Jurassic aquifers are dominantly sands or poorly cemented sandstones, and water movement is principally through the matrix. As rock sequences these strata comprise alternating sands and mudstones, frequently forming multi-aquifer systems. However, the layers are not always laterally persistent, adding to the complexity of the aquifer system.

The Upper Greensand Formation shows greater cementation than the older deposits, and therefore relies more on fracture flow.

The general hydrogeology is discussed in more detail in the sections on the individual aquifers.

5.1.3 Aquifer properties data availability

Aquifer properties data were largely obtained from Environment Agency licensing records, pumping test files, and reports. Misclassification of data is likely to be a problem with aquifers of this age, mainly due to lithological similarities between successive Lower Cretaceous formations. In Lincolnshire, there is evidence that tests carried out on the Carstone and Roach formations may have been erroneously attributed to the Spilsby Sandstone. In north Norfolk, pumping test results were only available for the Sandringham Sands aquifer, although the data were sometimes specific to the Leziate Beds. Again it is possible that tests carried out on minor aquifers above the Sandringham Sands Formation may have been misclassified as the latter.

5.1.4 General aquifer properties

Aquifer properties for most of the sandstones are a function of their lithological characteristics, due to the dominance of matrix flow. The Upper Greensand Formation tends to be more cemented than the other formations, and fracture flow may play a more important role. Possibly as a result, the transmissivities appear to have a greater range (25/75 percentiles of 6 to 419 m^2/d) than those for the Lower Cretaceous/Upper Jurassic formations of the Weald and eastern England (25/75 percentiles of 14 to 172 m^2/d). Storage coefficients for the Upper Greensand and the Lower Cretaceous/Upper Jurassic sands of the Weald show much more variation than those of eastern England, the latter tending to be much lower and a reflection of the generally confined conditions of the aquifer in this area. Of the Lower Cretaceous/Upper Jurassic sands, the Tunbridge Wells Formation has lower transmissivity and specific capacity values than the rest of the formations, suggesting it is a less productive aquifer (see Section 5.3.3).

5.2 THE UPPER GREENSAND FORMATION

5.2.1 Introduction

The Upper Greensand Formation underlies the Chalk in southern England. It overlies the Gault Clay Formation although the two formations were deposited together during the Albian. The latter name is used where the deposits are mostly clays and the former where sandy beds predominate, but in various parts of the country the Gault and Upper Greensand facies are shown by fossils to be temporally equivalent.

5.2.2 Geology and stratigraphy

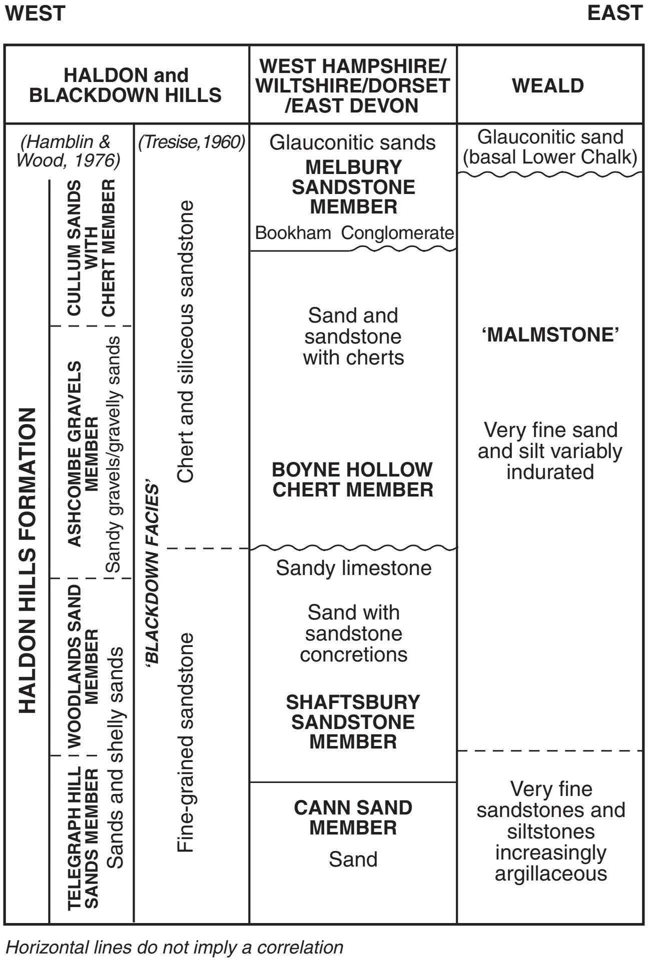
5.2.2.1 *Extent of aquifer group, stratigraphy and lithology*

The outcrops of the Upper Greensand Formation are long and narrow, both in the arc extending from the Haldon Hills to Dunstable and along the margins of the Weald west of a line drawn through Dunstable, Sevenoaks and Eastbourne. East of this line, the sediments are wholly in Gault Clay facies (Figure 5.1b). In the Weald, the Upper Greensand Formation reaches a maximum thickness of 45 to 60 m around Selborne. It thins to the west over the Hampshire-Dieppe High (the Portsdown Swell), and thickens again (up to 40 m) into the Channel/Vectian Basin, where up to 60 m of strata are present in the Haldon and Blackdown hills.

The Gault Clay-Upper Greensand formations overstep westwards onto successively older beds, from the Lower Greensand Group in the Isle of Wight area, onto Jurassic formations in Dorset and the Triassic in Devon.

The Upper Greensand Formation is divided into two facies; the 'greensand' facies itself is regarded as a glauconitic, calcareous, generally fine-grained sandstone, although it becomes coarser in the Haldon and Blackdown hills. The 'malmstone' facies is also a fine grained, often calcareous sandstone with abundant sponge spicules and a high proportion of colloidal silica (Rawson, 1992). The Upper Greensand Formation is divided into four main geographical areas: the Weald, the Chilterns, west Hampshire, Wiltshire and east Dorset, and the Blackdown and Haldon hills (west Dorset and Devon). Regional variations are illustrated in Table 5.2 and described in the following sections.

Table 5.2 Upper Greensand Formation stratigraphic terminology in southern England.



WEST **EAST**

HALDON and BLACKDOWN HILLS		WEST HAMPSHIRE/ WILTSHIRE/DORSET /EAST DEVON	WEALD
(Hamblin & Wood, 1976)	*(Tresise,1960)*	Glauconitic sands **MELBURY SANDSTONE MEMBER** Bookham Conglomerate	Glauconitic sand (basal Lower Chalk)
HALDON HILLS FORMATION **CULLUM SANDS WITH CHERT MEMBER**	*'BLACKDOWN FACIES'* Chert and siliceous sandstone	Sand and sandstone with cherts **BOYNE HOLLOW CHERT MEMBER**	**'MALMSTONE'** Very fine sand and silt variably indurated
ASHCOMBE GRAVELS MEMBER Sandy gravels/gravelly sands			
WOODLANDS SAND MEMBER Sands and shelly sands	Fine-grained sandstone	Sandy limestone Sand with sandstone concretions **SHAFTSBURY SANDSTONE MEMBER**	
TELEGRAPH HILL SANDS MEMBER		**CANN SAND MEMBER** Sand	Very fine sandstones and siltstones increasingly argillaceous

Horizontal lines do not imply a correlation

Weald

In the Weald area the Upper Greensand Formation has been informally divided into two units, an upper calcareous and micaceous 'malmstone' (very fine sandstone to siltstone) and a lower non-calcareous silty 'malm'. The malm beds form the majority of the formation; the malmstone beds appearing as discontinuous lenticular masses. It cannot be demonstrated whether the latter represent a single horizon of discontinuous lenses or a number of such bodies at different levels in the sequence, but they appear to be concentrated in the higher part of the formation (Rawson, 1992).

Chilterns

In the Chilterns, as far south as Henley and Newbury, the Upper Greensand Formation is similar in terms of facies to that of the Weald. South and west of Newbury there is a gradual increase in calcareous sandstones in the sequence.

West Hampshire, Wiltshire and east Dorset

In west Hampshire, Wiltshire and east Dorset, the Upper Greensand Formation has been divided into four members, the Melbury Sandstone Member, the Boyne Hollow Chert Member, the Shaftesbury Sandstone Member and the Cann Sand Member (Table 5.2).

Blackdown and Haldon hills (west Dorset and Devon)

The strata in west Dorset and Devon are lithologically distinct from those of the Upper Greensand Formation in the east, being coarser, non-calcareous and with significant pebble and shell beds. Known as the 'Blackdown facies' (Tresise, 1960), the sequence may be subdivided into two informal units: a lower unit of fine-grained sands overlain by an upper unit of glauconitic, poorly-sorted sands with chert. Hamblin and Wood (1976) proposed a formal division of the Upper Greensand Formation of the Haldon Hills into four members (Table 5.2).

5.2.2.2 *Depositional history*

The Upper Greensand Formation in the Wessex Basin represents an influx of sand during late Albian times. The diachronous Gault Clay Formation was deposited mainly as an outer shelf mud facies. However, along the western margins of the Wessex Basin, parts of the Lower Gault become increasingly silty, this being a forerunner of the input of sand that marks the deposition of the Upper Greensand. The sand prograded progressively to the east, so that the base of the formation youngs in that direction. East of a line through Dunstable, Sevenoaks, and Eastbourne (see Figure 5.1b), the late Albian sediments are all in Gault Clay facies (Rawson, 1992).

5.2.3 Hydrogeology

5.2.3.1 *Introduction*

The Upper Greensand Formation is an important minor aquifer in southern England. It is often found in hydraulic continuity with the overlying Chalk aquifer, and when this occurs they are usually considered together as a single aquifer unit (see Allen et al., 1997). However, where it is at outcrop or beneath a limited thickness of Lower Chalk, or where the Chalk is absent (as in the Vale of Pewsey), the Upper Greensand Formation may be an aquifer in its own right. The Gault Clay facies underlying or replacing the Greensand facies generally acts as an aquiclude.

Weald

As an aquifer, the Upper Greensand Formation is best developed at the western end of the Weald between Farnham and Petersfield and in places along the southern edge of the Weald. Between Bentley and Petersfield, the outcrops form a significant escarpment up to 60 m high. A number of road cuttings through this create substantial vertical sided rocky outcrops which show well fissured, fine grained glauconitic sandstone. The extensive dip slope area to the west is overlain with Lower Chalk extending as an eroded plateau beyond the Upper and Middle Chalk escarpment. Copious springs issue from the base of the Upper Greensand escarpment, but it is probable that on a regional scale much of the water is derived from the overlying Chalk, since the Upper Greensand has too narrow an outcrops to have an effective catchment area. An extensive study was made of the aquifer and its relationship with the Chalk in the Alton, Farringdon, Selborne area (Hunter, 1992). Three pairs of 200 mm diameter boreholes were separately drilled into the Lower Chalk and confined Upper Greensand respectively. Each was test pumped with stepped and constant rate tests. In no case did the adjacent aquifer respond to the pumping, indicating that locally the confined Upper Greensand was effectively separated from the main Chalk aquifer by the clay-rich basal Lower Chalk. Constant rate test yields ranged from 70 to 1037 m^3/d for the three Upper Greensand boreholes. Transmissivity values taken from good observation borehole data averaged 200 m^2/d with a storage coefficient of 3.12×10^{-4}.

A small number of licensed abstractions in the confined aquifer are also open to the Lower Chalk. Geophysical logging has confirmed that significant quantities, up to 800 m^3/d are obtained from the confined Upper Greensand. The groundwater quality in the western Weald is generally good (Adams, 1992) being a sodium/potassium type water with electrical conductivity typically between 500 and 600 µs/cm.

In general, yields from shallow wells located on the escarpment slopes around the Weald are low and fluctuating. However, around Steyning in Sussex the strata are thick and specific capacities can be high, for example a borehole of 300 mm diameter was recorded as having a specific capacity of 700 $m^3/d/m$ (Young and Lake, 1988).

Chilterns

In the area between Wendover and the Goring Gap, the Upper Greensand forms a substantial minor aquifer both as confined and unconfined strata. In places, a significant escarpment, about 40 m high, exists at distances of up to 5 km to the north-west of the main Chalk escarpment. This provides substantial outcrop area, allowing significant recharge to the aquifer and creating many scarp slope and several dip slope springs. A late winter/spring survey (January to March 1988) between Benson and Chinnor (Banks, 1989) described 44 springs. Many were perennial with gauged flows of several megalitres per day. The springs at Adwell [SU 697 992] were described as ‘enormously impressive’ with estimated winter flows of 8000 m^3/d. Throughout the area numerous catchpits and occasional ram pumps were observed. Where the Upper Greensand is thinly confined by Lower Chalk, there are four public water supply sources; these are at Britwell [SU 669 933], Watlington [SU 691 942], Lewknor [SU 711 964] and Kingston Blount [SU 744 982]. There is also one commercial source at Ewelme [SU 645 905].

In three cases the sources are open to both Lower Chalk and Upper Greensand, but the lower aquifer appears to be the most consistently productive (Robinson, 1989). At Kingston Blount Pumping Station extensive test pumping (Robinson, 1992; Gatesman et al., 1992) in both the unconfined Lower Chalk and confined Upper Greensand aquifers has demonstrated conclusively the hydraulic separation between the two aquifers. The separating layer is the basal 20 m of very clay-rich Lower Chalk beneath the Risborough Rock hard band. Test pumping at rates up to 2600 m^3/d and a licensed abstraction of 2270 m^3/d indicate the relative importance of this aquifer. Typical average output from all five sources is 5000 m^3/d mostly from the Upper Greensand. Aquifer parameters calculated from several pumping tests range from 300 to 690 m^2/d for transmissivity and from 8.1×10^{-4} to 1.1×10^{-3} for storage coefficient. At the two exclusive confined Upper Greensand sites, both geophysical logging and CCTV inspection have confirmed that groundwater is derived from only two or three productive fissures in the top 10 m of the aquifer. Groundwater quality analyses show a dominantly sodium bicarbonate type indicating that the Chalk and Upper Greensand aquifers are locally separate.

West Hampshire, Wiltshire and east Dorset

Around the escarpment of the Berkshire and Wiltshire downs, in the Vale of White Horse and in Wiltshire between Wroughton (south of Swindon) and Calne in Wiltshire, the Upper Greensand has a narrow outcrop and is dominated by the Malm facies becoming more clayey to the west. It supports only a few small springs, some of them difficult to separate from the Chalk nearby, and only a few shallow wells, most of which are disused. South-west of Avebury and into the Vale of Pewsey the Upper Greensand facies becomes very sandy, once more supporting numerous springs in the Vale of Pewsey; here it becomes better aquifer. Further south-west it becomes an important water-bearing formation in Dorset and Wiltshire, despite being of no great thickness, and with only a moderate area of outcrop. The formation is highly permeable, consisting of alternating sand and sandstone, with a little chert. Some beds are much more permeable than others. The Upper Greensand is the principal source of groundwater in much of the area; springs are used both for public supply and watercress beds.

Around Shaftesbury, the Upper Greensand Formation is also the main aquifer of the district, supporting seven public supply sources at Barton Hill [ST 864 232], Donhead [ST 8999 2298], Boyne Hollow [ST 8730 2210] and [ST 8749 2179], Berwick St John [ST 9415 2182], Buckland Newton [ST 6853 0597], Ibberton [ST 7893 0759] and Cookwell Spring [ST 8049 1061] as well as several private supplies. Springs are commonly used for abstraction. They are not restricted to the junction with the Gault, but issue at various levels within the formation depending on local topography and hydrogeology. Those at Boyne Hollow yielded 1220 m^3/d in 1961, and those at Buckland Newton in excess of 430 m^3/d. Up to 1500 m^3/d is obtainable from the two boreholes at Barton Hill. Yields of up to 85 m^3/d are common from small springs or boreholes at the Upper Greensand/Chalk junction.

Isle of Wight

On the Isle of Wight up to 40 m of Upper Greensand has impressive coastal outcrops along the south coast in the form of cliffs showing alternating bands of hard chert in between softer sandstone layers. These overlie the sandy Malm facies (also known locally as the Passage Beds). All layers are well jointed vertically. Strong springs at the junction with the Gault Clay have resulted in large areas of coastal landslips and foundered strata. Elsewhere on the island there are considerable areas confined beneath the Chalk. There appears to be good hydraulic continuity with the joints and fissures in the overlying Chalk. In the southern part of the island where the Chalk caps the high ground, the Chalk aquifer is generally unsaturated, and the Upper Greensand beneath acts by ‘proxy’ as the reservoir for Chalk recharge (Packman, 1996). It is not surprising therefore that there are a number of public water supply sources from this aquifer and clearly this aquifer is of great importance on the Isle of Wight.

At Bowcombe near Carisbrooke, two boreholes are licensed for 2575 m^3/d. At Ventnor, the old railway tunnel has created a spring source which, combined with a local borehole is licensed for 3795 m^3/d. Other sources exclusively in the Upper Greensand are at Niton and Chillerton. There are also sources open to both the Chalk and Upper Greensand combined because of the continuity between the two aquifers. Small spring sources exit at St Lawrence, Luccombe and Brighstone.

Groundwater chemistry is indistinguishable from the Chalk aquifer demonstrating hydraulic continuity between the formations.

Blackdown and Haldon hills (West Dorset and Devon)

The Upper Greensand Formation is an important source of water in the district. In the Blackdown Hills numerous springs occur at the boundary with the Mercia Mudstone Group or Lias, and these are often used for water supply. Due to the slight south-easterly dip of the Cretaceous strata, the majority of springs occur along the slopes facing east and south-east, rather than the slopes facing west and north-west. The Upper Greensand in the Halden Hills overlies Permian conglomerates.

5.2.3.2 *Core data*

Hydraulic conductivity data for the Upper Greensand Formation are relatively numerous and are displayed in Figure 5.4 and summarised in Table 5.3. Fifty eight of the core samples were taken from deep horizons (below 125 m depth) and in part this explains the bimodal data distribution. Figure 5.5 shows that samples from less than 125 m depth mostly have hydraulic conductivities greater than

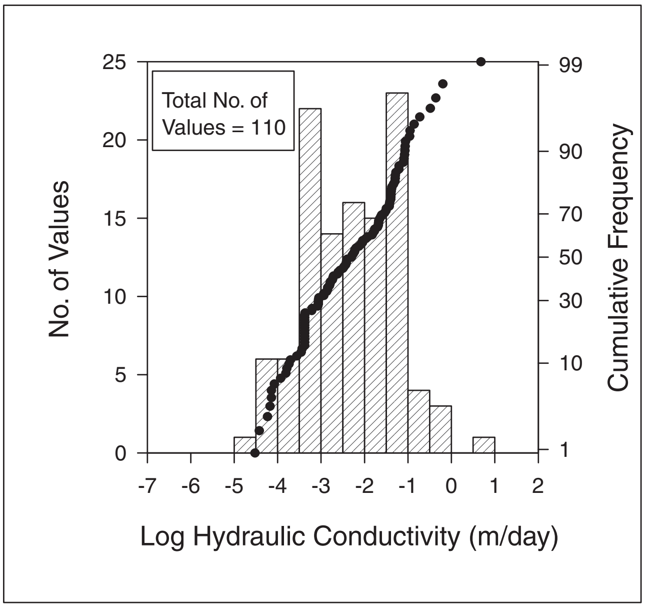


Figure 5.4 Distribution of hydraulic conductivity values from core samples in the Upper Greensand Formation.

Table 5.3 Summary of hydraulic conductivity and porosity data from Upper Greensand Formation core samples.

Upper Greensand Formation		
Total number of records	115	—
Number of hydraulic conductivity records	110	—
Minimum/maximum hydraulic conductivity (m/d)	3×10^{-5}	4.78
Arithmetic/geometric mean of hydraulic conductivity (m/d)	7.6×10^{-2}	5.0×10^{-3}
Median/interquartile range of hydraulic conductivity (m/d)	4.0×10^{-3}	4.0×10^{-2}
25/75 percentile of hydraulic conductivity (m/d)	4.0×10^{-4}	3.8×10^{-2}
Number of porosity records	111	—
Minimum/maximum porosity	3.21	52.9
Arithmetic/geometric mean of porosity	30.5	27.5
Median/interquartile range of porosity	29.9	14.0
25/75 percentile of porosity	22.6	36.6

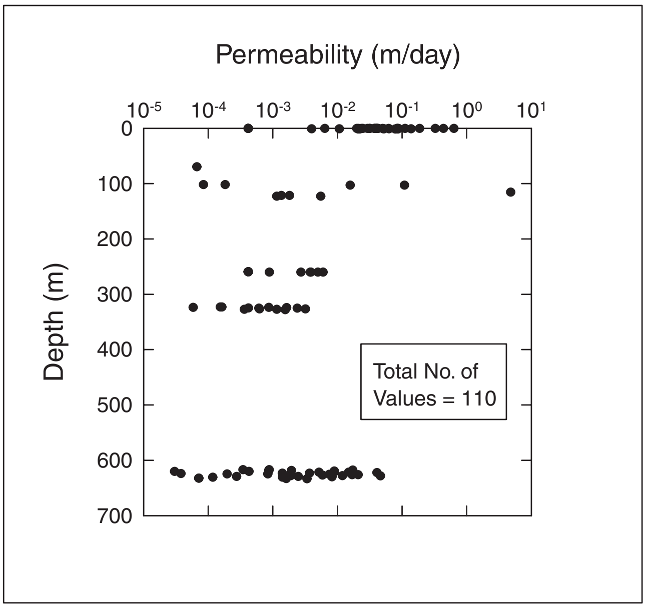


Figure 5.5 Permeability variation with depth in the Upper Greensand Formation.

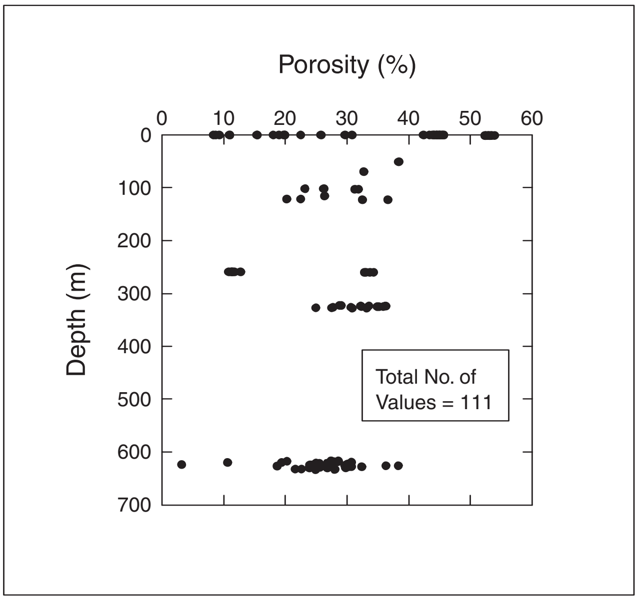


Figure 5.7 Porosity variation with depth in the Upper Greensand Formation.

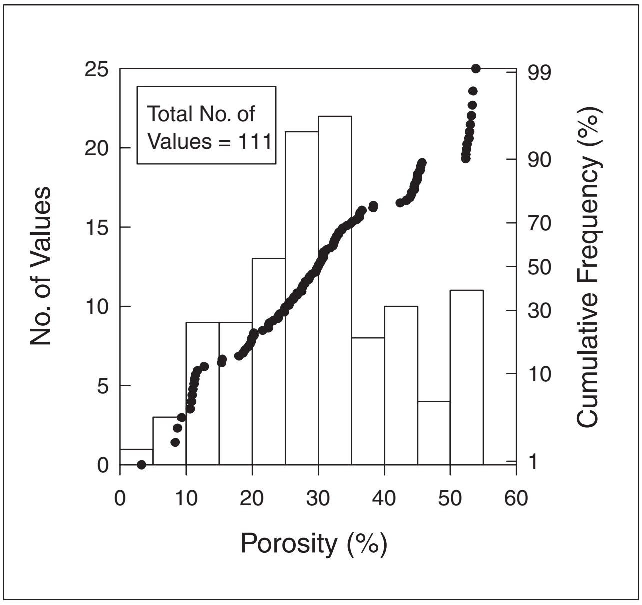


Figure 5.6 Distribution of porosity values from core samples in the Upper Greensand Formation.

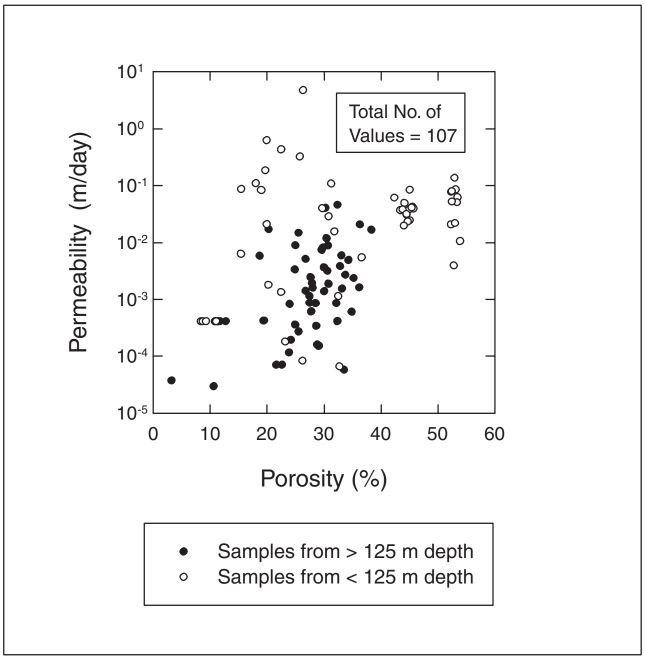


Figure 5.8 Crossplot of permeability against porosity for core samples from the Upper Greensand Formation.

0.001 m/d and often greater than 0.01 m/d. In contrast, those from greater depths are generally less than 0.01 m/d. These hydraulic conductivity values are quite low, being in the range of those which might be expected for an unconsolidated silty sand (Freeze and Cherry, 1979).

Total interconnected porosity values are closer to a log-normal distribution (Figure 5.6) with an interquartile range typically between 23 and 37%, although there were a relatively high number of samples with porosities greater than 50%. The porosities are high for a sandstone and imply little reduction in effective porosity due to cementation. Figure 5.7 shows that the samples from above 125 m depth have a much wider porosity range but are not necessarily less porous than their counterparts at depth. The fact that there is such storage potentially available may have future resource implications.

Figure 5.8 shows that there is no significant correlation between permeability and porosity for samples from less than 125 m depth, although there may be a slight positive correlation for samples from greater than 125 m.

5.2.3.3 *Pumping test results*

Statistical summaries of the pumping test data are shown in Table 5.4. Transmissivity, specific capacity and storage coefficient distributions are shown in Figures 5.9, 5.10 and 5.11 respectively. The range of transmissivity values is wide (1 to 1565 m^2/d), although it is affected by two very

Table 5.4 Summary of pumping test results for the Upper Greensand Formation.

Upper Greensand Formation records		
Total number of records	57	—
Number of transmissivity values	28	—
Minimum/maximum transmissivity value (m^2/d)	1.24	1565
Arithmetic/geometric mean of transmissivity (m^2/d)	276	64.0
Median/interquartile range of transmissivity (m^2/d)	100	413
25/75 percentile of transmissivity (m^2/d)	5.9	419
Number of storage coefficient values	10	—
Minimum/maximum storage coefficient value	0.0002	0.013
Number of specific capacity values	43	—
Minimum/maximum specific capacity value (m^3/d/m)	1.54	3162
Arithmetic/geometric mean of specific capacity (m^3/d/m)	164	39.6
Median/interquartile range specific capacity (m^3/d/m)	43.2	147
25/75 percentile of specific capacity (m^3/d/m)	12.6	160

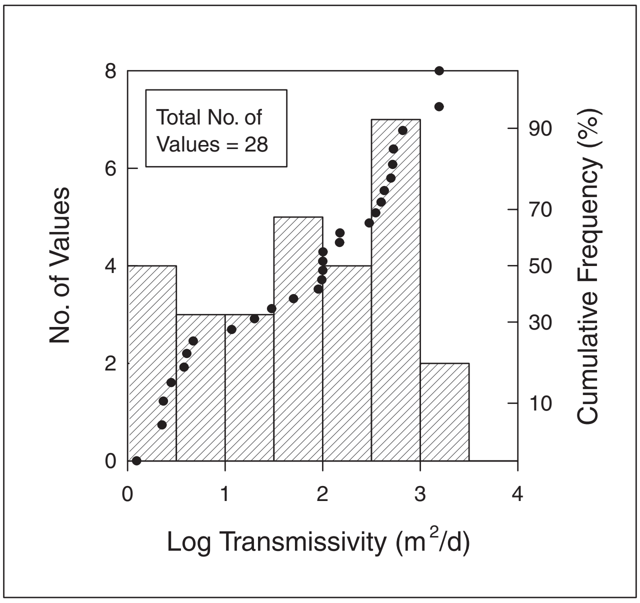


Figure 5.9 Distribution of transmissivity values from pumping tests in the Upper Greensand Formation.

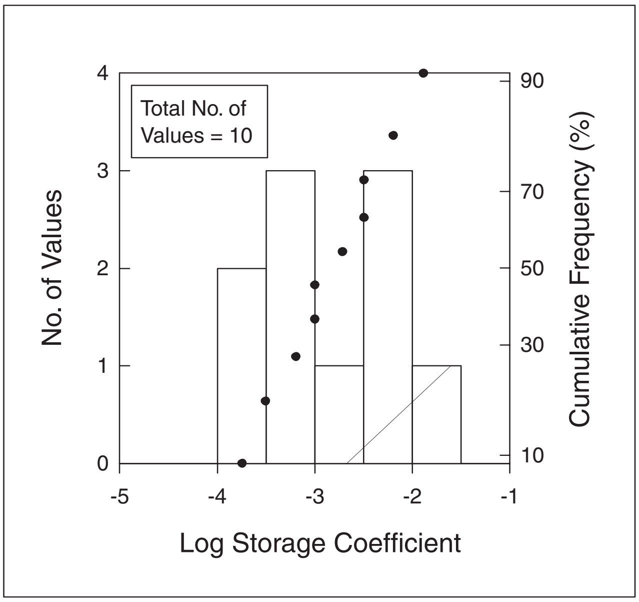


Figure 5.11 Distribution of storage coefficient values from pumping tests in the Upper Greensand Formation.

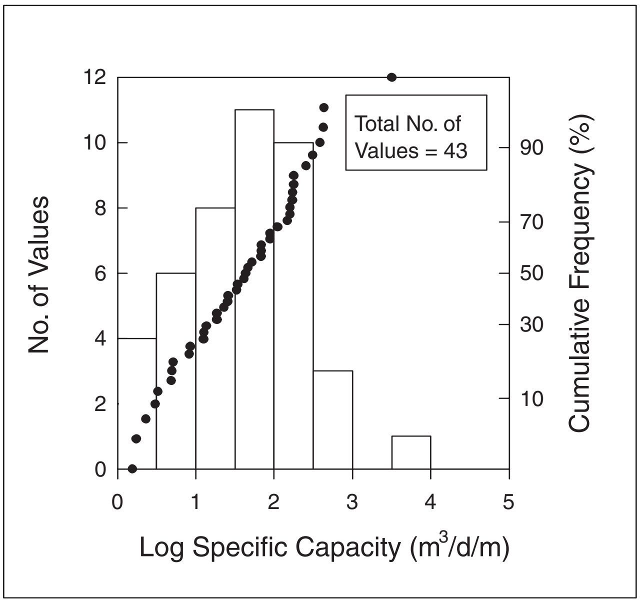


Figure 5.10 Distribution of specific capacity values from pumping tests in the Upper Greensand Formation.

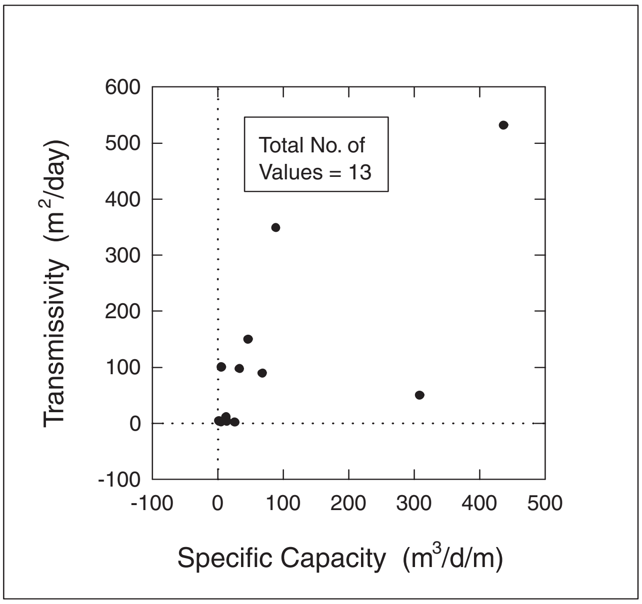


Figure 5.12 Correlation between transmissivity and specific capacity for the Upper Greensand Formation.

high values at Severalls Farm [SU 59660 91500] and St Alban's Quarry [SU 64590 90480]. The remainder of the values are less than 650 m^2/d. The geometric mean is 64 m^2/d, and the interquartile range is 6 to 420 m^2/d. The data do not appear to have a well defined distribution. Similarly to the transmissivity data, the wide range of specific capacities is unduly influenced by the very high value at Severalls Farm (316 m^3/d/m), the remainder of the values being less than 450 m^3/d/m. The interquartile range again reflects the predominantly lower values, being 12.6 to 160 m^3/d/m. The data show an approximately log-normal distribution. Storage coefficients vary from 0.0002 to 0.013, suggesting both confined and unconfined conditions exist.

The variation in transmissivity values does not appear to be closely related to geographical location and hence lithological variation between the different areas of the Upper Greensand. Whilst it might be expected that the highest transmissivity values would occur in the south-west where the lithology is most arenaceous, in reality the highest values are found in the Dorset/Wiltshire and Chilterns areas. Comparison between transmissivity and specific capacity and the thickness of the aquifer also fails to show any correlation.

5.3 THE LOWER CRETACEOUS/UPPER JURASSIC OF THE WEALD

5.3.1 Introduction

The Weald covers an area of approximately 5000 km^2 and includes much of the counties of Kent, East and West Sussex and the south-eastern part of Surrey. The rocks of the Wealden Basin extend beneath the Upper Cretaceous at depth to the west as far as Winchester and the easternmost part of Hampshire, with the feather edge extending even further westward perhaps as far as the Vale of Wardour. The rocks of the Weald are also found at depth beneath the North and South Downs. To the north their extent and thickness is progressively limited by step-like normal faulting to the north against the London–Brabant Ridge, whilst to the south they thin rapidly against the Hampshire–Dieppe (Portsdown) High.

5.3.2 Geology and stratigraphy

5.3.2.1 *Extent of aquifer group, stratigraphy and lithology*

In the Wealden Basin two main groups are identified in the sequence considered to be the Wealden. A lower Hastings Group of predominantly ferruginous sandstones, siltstones and shales is overlain by a principally argillaceous sequence called the Weald Clay Group. The Purbeck Group, which passes up conformably into the Hastings Group has an upper part (the Durlston Formation) which is also of Lower Cretaceous age. The Purbeck Group as a whole is dealt with in the Jurassic chapter (Chapter 6) of this volume. The Weald Clay Group is separated from the overlying Lower Greensand Group by an unconformity (Table 5.1).

In the Hastings Group, the thick, arenaceous Ashdown and Tunbridge Wells formations are separated over the whole Weald by a transgressive argillaceous unit, the Wadhurst Clay Formation. A later transgression in the western Weald is marked by the Grinstead Clay Formation, which divides the sands of the Tunbridge Wells Formation before petering out eastwards. Hence in the eastern Weald the upper and lower members of the Tunbridge Wells Formation cannot be separated.

Although these major units can be placed in vertical succession their boundaries are diachronous; the vertical lithological changes represent three major coarsening-upward cycles. Superimposed on this broad cyclicity is a smaller-scale cyclicity which, coupled with lateral facies changes, results in the recognition of numerous minor, local subdivisions within the Hastings Group.

Ashdown Formation

The Ashdown Formation extends eastwards from Horsted Keynes [TQ 38 28], where it forms the Ashdown Forest, and east-south-eastwards through Heathfield and Battle to the coast. The outcrop is not continuous, consisting not only of two masses, the Ashdown Forest and the district from Uckfield [TQ 47 21] to Winchelsea [TQ 90 17], separated by a ridge of overlying rocks, but also of a large number of inliers due to erosion and faulting. Figure 5.13 shows the outcrop of the Ashdown and Tunbridge Wells formations, and illustrates the marked influence of faulting on the outcrop pattern of the formation. From borehole evidence, the full thickness in the Ashdown Forest area is approximately 210 to 230 m; the beds thin to the north and south, where the thickness is around 180 m. On the western edges of Ashdown Forest the highest 60 m of the formation is brought to the surface by the Crowborough Anticline.

The Ashdown Formation consists of fine-grained, silty sandstones and siltstones with subordinate shale and mudstone. Within the area of its outcrop the formation shows a regular lithological variation, and exhibits, on a reduced scale, the rhythmic deposition characteristic of the whole Wealden succession. In south-east Sussex, around Hastings, the argillaceous parts of the cyclothems are well developed and a series of clay seams, the Fairlight Clays, is present. Northwards from Hastings the Fairlight Clays become steadily thinner and in the Ashdown Forest they are represented only by pebble beds overlain by thin siltstone beds. The top 50 m of the formation is predominantly sandstone.

Wadhurst Clay Formation

The Wadhurst Clay Formation comprises grey-green clays and silty shales with thin sandstone and limestone beds, reaching up to about 60 m in thickness. It outcrops between the Ashdown Formation and Tunbridge Wells Formation, forming a rough horseshoe shape. The continuity of the outcrop is broken by faults and the clay rarely covers a wide and continuous expanse, partly due to the presence of outliers of the overlying Tunbridge Wells Formation, and to the erosion of valleys through the soft shales to the underlying Ashdown Sand.

The base of the Wadhurst Clay Formation is usually marked by a pebble bed called the Top Ashdown Pebble Bed, and the top by a thin band of red shales. Localised sand units occur within the Wadhurst Clay Formation, such as the Cliff End Sandstone.

Tunbridge Wells Formation

The outcrop of the Tunbridge Wells Formation is also horse-shoe shaped, with the bend at Horsham; the northern limb passes through East Grinstead and Frant [TQ 59 39], and the southern limb through Cuckfield [TQ 30 24], Uckfield [TQ 47 21] and Hellingly [TQ 58 12]. The outcrop is less broken by faults than that of the Ashdown Formation, but many small outliers occur, and the main outcrop is much smaller than the total. As in the Ashdown Formation, beds of clay are frequently developed; a significant one, the Grinstead Clay Formation, divides the Tunbridge Wells Formation, in the western part of the outcrop, into Upper

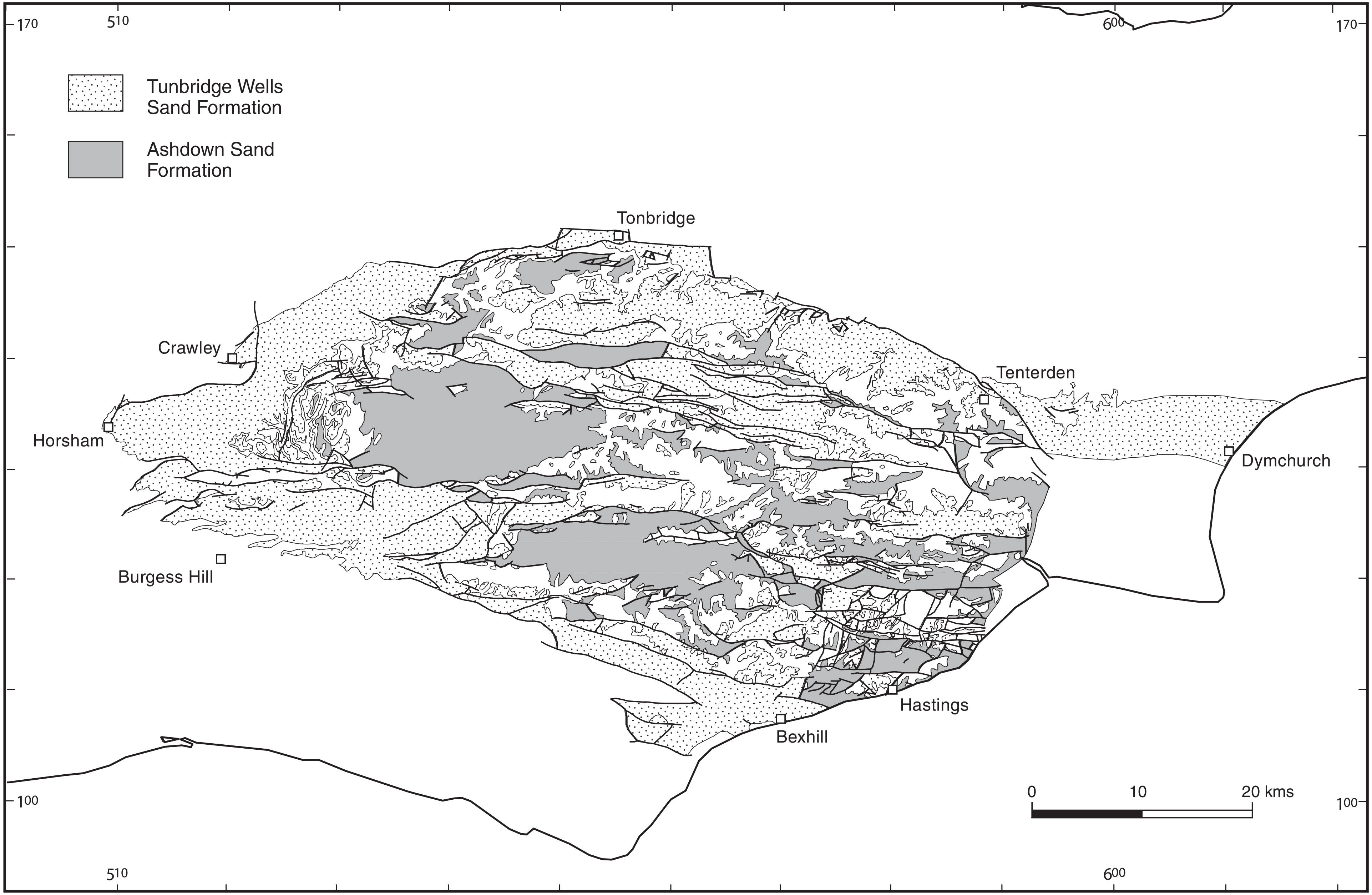


Figure 5.13 Outcrop of the Hastings Group aquifers of the Weald.

and Lower divisions. To the east however, while clay beds are developed, they are of less importance, and the main mass is undivided. Within the argillaceous beds of the Grinstead Clay Formation, localised sand units occur, principally the Cuckfield Stone.

The Lower Tunbridge Wells Formation can be divided into two parts: a lower unit of interbedded silts and fine sandstones, overlain by a massive clean white sandstone, the Ardingly Sandstone, which gives rise to an impressive line of crags. The Upper Tunbridge Wells Formation is lithologically similar to the lower part of the Lower Tunbridge Wells Formation, consisting of mudstones, silts and sandstones. The sandy facies of the Tunbridge Wells Formation lithologically resembles the Ashdown Formation. In addition to the Grinstead Clay Formation, numerous small seams of clay are developed, which affect groundwater flow by dividing the sandy facies into smaller units. Occasionally the sandy facies appear to be replaced locally entirely by clay.

5.3.2.2 *Depositional history*

The nature of the Wealden environment is still a matter of debate. Allen (1976; 1981) postulated that the Wessex Basin was a shallow embayment opening into a Boreal Sea (Figure 5.14). Increased erosion of the surrounding uplands (the London Platform and the Armorican and Cornubian massifs) resulted in bursts of arenaceous sedimentation into a low lying plain central to the basin (dominated by argillaceous meander-plain deposits). On occasion, rapid transgression of brackish lagoonal conditions from the north-west covered much of the basin leading to the deposition of silts and clays.

Two major cycles of sedimentation (megacyclothems of Allen, 1959) are recognised within the Hastings Group, with a third possibly represented by the Upper Tunbridge Wells Formation and the lower part of the Weald Clay Group. Each cycle consists of claystone and mudstone coarsening upwards into cross-bedded sandstone in the lower part, this being separated from a fining upward siltstone to mudstone upper part by a pebble bed sitting on a marked erosion surface. These upper argillaceous (transgressive from the north-west) beds are represented in the Weald by the Wadhurst Clay Formation, which covers the whole of the basin, and the Grinstead Clay Formation which peters out eastward between Tunbridge Wells and Tenterden [TQ 88 33].

Sedimentologically the lower part of each cycle in the Hastings Group represents a change upward from deposition in a gently meandering to braided channel fluvial systems whilst the upper argillaceous part represents deposition in what has been termed a 'mudplain', presumably shallow water generally more brackish lagoonal sequences with fringing reed swamps and soil horizons. Sand bodies in these upper argillaceous units may represent barrier bar, channel fill or small scale fan deltas. The depositional style and environment probably mean that lithological boundaries, certainly for the major units, are diachronous across the basin and that continuity of beds on a local scale can be variable.

The Weald Clay Group was deposited under less varied conditions than the Hastings Group and is characterised by two major cycles of sedimentation in a non-marine floodplain environment, with occasional marine incursions from the 'Boreal Sea' to the north. The group is split into lower and upper formations which roughly correspond to the Hauterivian and Barremian stages respectively. The Lower Weald Clay is characterised by small 'Paludina' and 'Cyrena' freshwater limestone and clay alternations, whilst the Upper Weald Clay contains limestones, and sandstone alternating with clay beds. Lithologically the Weald Clay consists principally of grey silty clay, dark grey shaley clay, brown clay, mottled clay, with beds of sandstone, freshwater limestone and ironstone.

The thickest deposits of the Weald Clay Group are in the area of the north-west and west Weald and it is generally this area that has the greatest frequency of sandstone, ironstone and limestone beds, representing fluviatile and brackish water incursions.

5.3.2.3 *Structural geology*

The rocks of the Weald are folded into a pericline with its major axis roughly from west-north-west to east-south-east. As a result of erosion of this pericline, the oldest rocks are exposed at the centre, away from which the beds dip in all

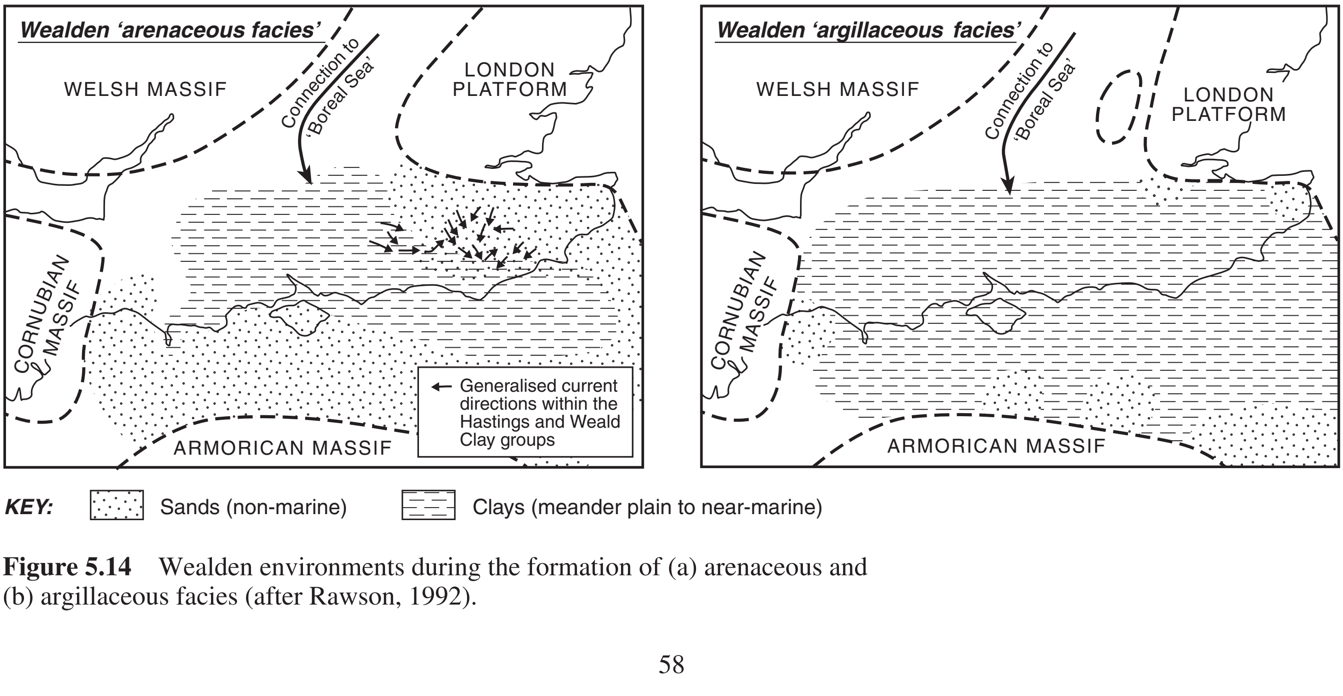


Figure 5.14 Wealden environments during the formation of (a) arenaceous and (b) argillaceous facies (after Rawson, 1992).

directions, with the youngest rocks at the edge. As well as the major anticlinal axis, other folds in the Weald are the Brightling Anticline on the southern margin of the basin, and the Crowborough Anticline in the north-west. Smaller-scale anticlines are also present, with associated synclines.

The structure of the Weald principally reflects the generally extensional regime of underlying faulting of the Jurassic strata. Step faulting and subsequent erosion associated with this extension limits the preserved thickness of the Wealden both to the north against the London Platform and to the south over the Hampshire/Dieppe High. Reactivation of these faults in the reverse sense, and low amplitude folding in the Early Neogene as the result of the 'Alpine' compression, has resulted in the complex block-like structure of the Wealden strata. Their continuity has been greatly affected by these later movements.

The Wealden strata are also known to be greatly affected by valley bulge and cambering, particularly in the central Weald. This process, mainly the result of Pleistocene periglacial erosion, can locally cause great disruption of strata, and groundwater flow through these disturbed sequences is very complicated.

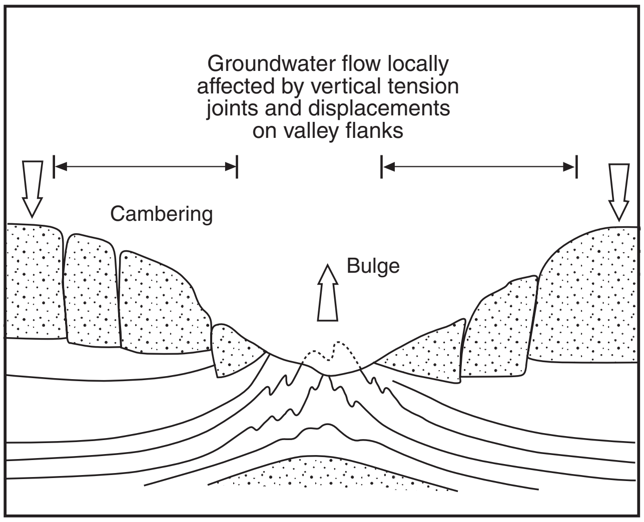


Figure 5.16 Valley bulging and associated movement (cambering) at valley sides (after Blyth and de Freitas, 1984).

Figure 5.15 illustrates the numerous faults and resulting structural complexity across the Weald. Figure 5.16 shows diagrammatically the local effects associated with competent bed movements as a result of valley bulge and cambering. The extensive faulting has hydrogeological implications as discussed in 5.3.3.10.

5.3.3 Hydrogeology

5.3.3.1 *Introduction*

The most significant aquifers in the Weald are the Ashdown Formation and the Tunbridge Wells Formation of the Hastings Group, with the former being the more important aquifer of the two. The two aquifers are separated by the Wadhurst Clay Formation, which generally acts as an aquiclude, confining the underlying Ashdown Formation.

The hydrogeology of the Ashdown Formation is complex and not well understood. The aquifer is thought to be a stack of discontinuous layers allowing groundwater movement between and through them. The lack of correlation of water levels even between closely situated boreholes is a further indication of a patchy, multi-layered aquifer, without a single water table.

The presence of faulting in the area causes large variations in water level, which have not been well studied or documented. Consequently, it is often difficult to predict the potentiometric levels in boreholes. In the Tunbridge Wells area, Tunbridge Wells Formation rest water levels range from 17 to 105 m AOD, with the highest level occurring beneath the highest ground (Bristow and Bazley, 1972). Seasonal fluctuations in the water table have also not been well documented; at Frant [TQ 632 356] the water level fluctuation is 2 m (Bristow and Bazley, 1972).

The top member of the Ashdown Formation, sometimes known as the Top Ashdown Pebble Bed, is considered to be the most permeable and to form the most important part of the aquifer. The Fairlight Clays, which form the lowest, clayey part of the Ashdown Formation are of little importance as an aquifer.

5.3.3.2 *Previous studies*

Detailed local studies of the Hastings Beds have been carried out by Eastbourne Waterworks Company (1979) and Southern Water Authority (1978; 1981). Conclusions from these studies have been referred to where appropriate.

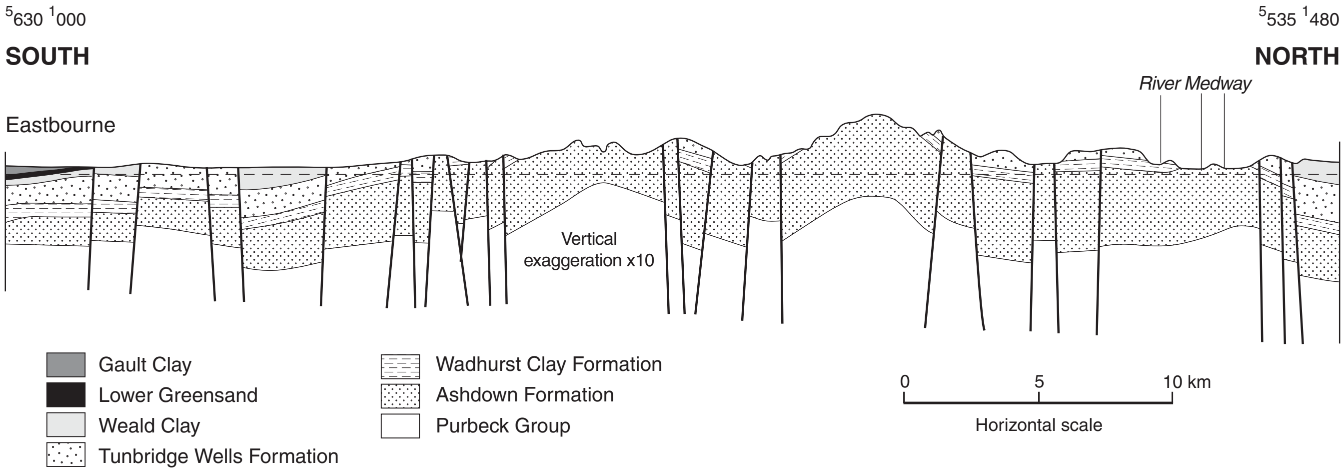


Figure 5.15 Cross-section across the Weald showing the effects of faulting.

5.3.3.3 *Groundwater flow and recharge*

A major influence on groundwater flow is the structural geology of the area. Groundwater tends to flow down dip towards the axes of synclines and away from the axes of anticlines. Also, major faults affect groundwater flow, although the actual effects may vary. Where faulting inhibits groundwater flow, rest water levels in boreholes either side of faults may be very different. For example, in the boreholes at Chase Wood [TQ 5929 3659], the rest water levels are higher and differ considerably from the rest water levels in a borehole to the south of the southernmost fault (Southern Water Authority, 1978). The impacts of faulting on the hydrogeological regime are discussed in Section 5.3.3.10. Topography also influences local groundwater flow patterns; that is, flows not constrained by structural influences will be directed from regions of high topography to regions of low topography.

Lithological variations within the Ashdown and Tunbridge Wells formations affect groundwater flow, as clay horizons split the sandstone into a multi-layered aquifer, often resulting in perched water tables.

Groundwater flow is further complicated as different segments of the same aquifer can become compartmentalised as a result of erosion, leaving blocks of aquifer isolated as erosional outliers.

Due to the general tectonic structure of the Weald (a pericline with the strata dipping away from the centre) little water enters from catchment areas from outside the district. Where the Ashdown Formation is confined by the Wadhurst Clay Formation, the recharge mechanism is unclear. Many major abstractions from the Ashdown Formation are some way from the outcrop, and it is thought that recharge may occur via fault-generated conduits between the sandstone layer in the Wadhurst Clay Formation and the Ashdown Formation, such as at Powdermill [TQ 7431 1496] (Eastbourne Waterworks Company, 1979). Faulting may also juxtapose the Ashdown Formation against the Tunbridge Wells Formation, allowing recharge to the Ashdown Formation to occur. This is thought to be a probability at Chase Wood (Southern Water Authority, 1978).

The Tunbridge Wells Formation is usually unconfined, and gives rise to a number of springs. At outcrop, this formation is responsible for providing the baseflow component to surface drainage, whilst the underlying confined Ashdown Formation, beneath the Wadhurst Clay Formation, constitutes the major resource.

5.3.3.4 *Nature and extent of confinement*

There are several major clay horizons which act as confining strata; many have subordinate sandstones or limestones which may act as local aquifers in themselves. The Hastings Group is confined by the overlying Weald Clay Group. The latter is essentially an impermeable, confining clay formation, although it contains thin, silty sandstones and limestones which may yield small local supplies.

West of Tunbridge, the Tunbridge Wells Formation is divided into Upper and Lower units by the Grinstead Clay Formation, which acts as an aquiclude. The Grinstead Clay Formation also contains a number of more permeable horizons of sandstone and limestone, including the relatively thick Cuckfield Stone in the Chiddingstone Heath region. However, these are rarely used for water supply.

The Wadhurst Clay Formation, between the Tunbridge Wells Formation and the Ashdown Formation, is also essentially an aquiclude, although again it contains thin sandstones and limestones from which supplies have been obtained. A 146 day pumping test in the Ashdown Formation at Maythem Farm [TQ 8667 2825] indicated that there is significant leakage from the Wadhurst Clay Formation; the slow rate of drawdown and recovery in that test indicated a depletion of storage in the Wadhurst Clay which arrested the drawdown in the Ashdown Formation. A long time was required to establish equilibrium, and also for the subsequent recovery (Southern Water Authority, 1978).

5.3.3.5 *Aquifer properties*

The aquifers within the Hastings Group contain a variety of lithologies which range in grain size from medium-grained sands to silty clays, and in degree of cementation from hard sandstone to poorly consolidated sand; hence groundwater flow varies greatly in type (both intergranular and fracture flow) and in rate. Available references are poor in this area and there is limited understanding of the relative importance of matrix and fracture flow. Aquifer thicknesses also vary and structural complexities arise as a result of the folding and faulting which have affected these beds. Consequently the forecasting of aquifer properties in these strata is difficult, and the chances of borehole success are rather less than in other, less complex, areas.

The Ashdown Formation is usually a more useful aquifer than the Tunbridge Wells Formation, but there are exceptions. For example, at Moatlands Golf Club [TQ 6729 4389], tests were conducted on each formation, and these indicated better hydraulic conductivity, transmissivity and storage coefficient for the Tunbridge Wells Formation (transmissivity of 22 to 47 m^2/d) than for the Ashdown Formation (transmissivity of 12 m^2/d).

Ashdown Formation

Dynamco (unpublished internal file note, 1992) suggested that for productivity classification purposes, the following ranges of transmissivity values for the Ashdown Formation were applicable:

Excellent	> 150 m^2/d
Good	120–150 m^2/d
Poor	100 m^2/d
Low	< 50 m^2/d

Where a site is being considered for public supply, sites with a transmissivity value of less than 100 m^2/d will rarely be considered. A general storage coefficient for the confined Ashdown Formation is cited as around 10^{-4}.

Previous studies (Southern Water Authority, 1978) indicated that higher transmissivity values are expected where the Ashdown Formation is confined by the Wadhurst Clay Formation, as here the top 15 m of the aquifer is present, which is thought to be the most permeable part of the formation (see Section 5.3.3.8). Southern Water Authority (1978) suggested transmissivity values generally fell between 120 to 160 m^2/d with a storage coefficient of 10^{-4} for the confined Ashdown Formation. Where the aquifer was unconfined, lower transmissivity values of less than 60 m^2/d were expected. In the Ashburnham area (Lake and Shephard-Thorn, 1987), mean transmissivity values of 120 m^2/d were obtained with a corresponding storage coefficient of 1.4×10^{-4}.

Tunbridge Wells Formation

A hydraulic conductivity of 4 m/d was estimated at the Chart Hills Golf Club [TQ 854 410] from the measured pumping test transmissivity. It was assumed for this estimate that the

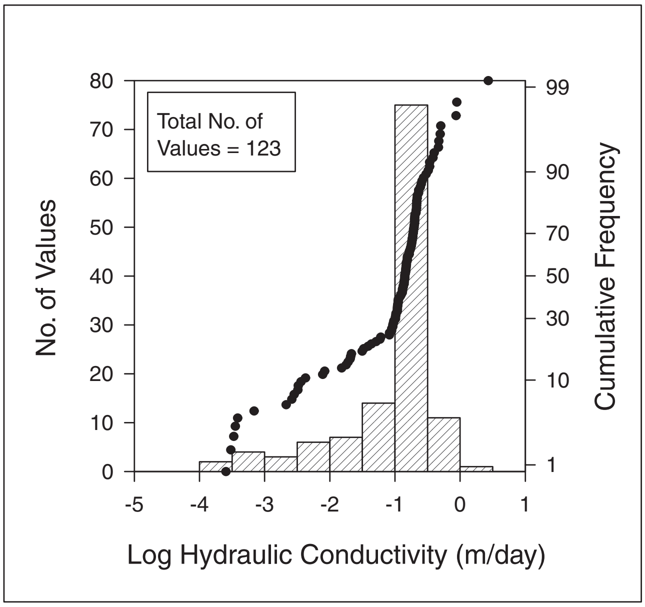


Figure 5.17 Distribution of hydraulic conductivity values from core samples in Wealden strata.

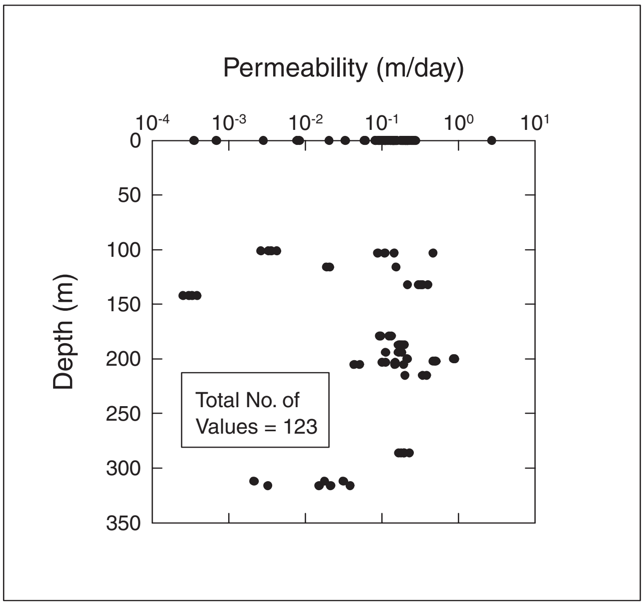


Figure 5.18 Permeability variations with depth in Wealden strata.

aquifer was 6 m thick, as the main water-bearing strata in all three boreholes at the site was a sand zone of this thickness.

5.3.3.6 *Core data*

Values of core permeability for the Weald are illustrated in Figure 5.17 and summarised in Table 5.5; the formations within the Weald from which the samples have been taken are not distinguished but are likely to be from the Hastings Group. Values of hydraulic conductivity are relatively high, with a geometric mean of 0.08 m/d, and range of 2.5×10^{-4} to 2.71 m/d. The interquartile range is very narrow (from 0.09 to 0.20 m/d), suggesting a very homogeneous group of aquifers. The data distribution has a slight negative skew.

Figure 5.18 shows the variation in hydraulic conductivity with depth for the Cuckfield No. 1 Borehole [TQ 296 273]. The samples taken from quarries (shown as 0 m depth) have a very wide range of permeability values, possibly as a result of weathering. For the Cuckfield borehole, there is no obvious pattern of decline in permeability with depth. Depth samples were taken of both the Ashdown and Tunbridge Wells formations, although the sampling was too infrequent to ascertain any difference in permeability

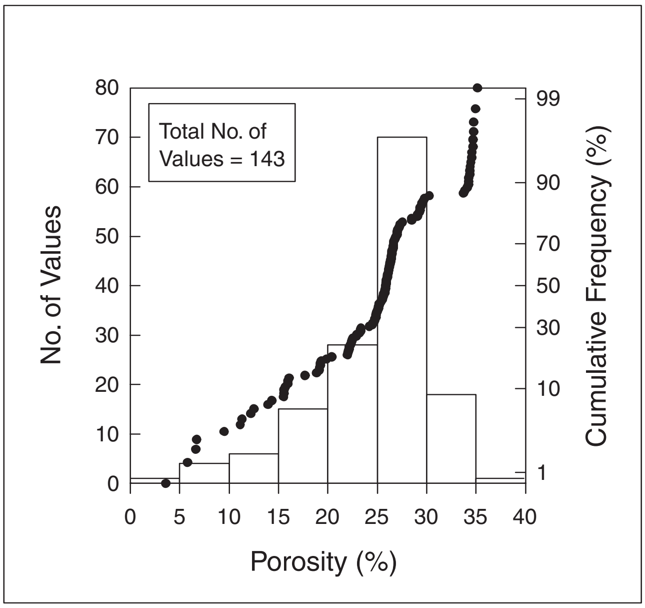


Figure 5.19 Distribution of porosity values from core samples in Wealden strata.

Table 5.5 Summary of hydraulic conductivity data from core samples in Wealden strata.

Wealden Lower Cretaceous/Upper Jurassic strata		
Total number of records	143.	—
Number of hydraulic conductivity records	123	—
Minimum/maximum hydraulic conductivity (m/d)	2.5×10^{-4}	2.71
Arithmetic/geometric mean of hydraulic conductivity (m/d)	0.18	0.08
Median/interquartile range of hydraulic conductivity (m/d)	0.14	0.11
25/75 percentile of hydraulic conductivity (m/d)	0.09	0.20
Number of porosity records	143	—
Minimum/maximum porosity	3.59	35.1
Arithmetic/geometric mean of porosity	24.8	23.6
Median/interquartile range of porosity	25.9	4.57
25/75 percentile of porosity	22.5	25.9

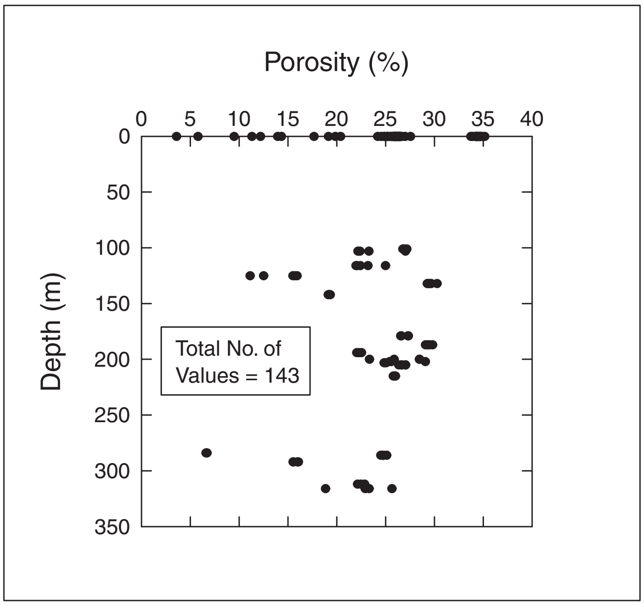


Figure 5.20 Porosity variations with depth in Wealden strata.

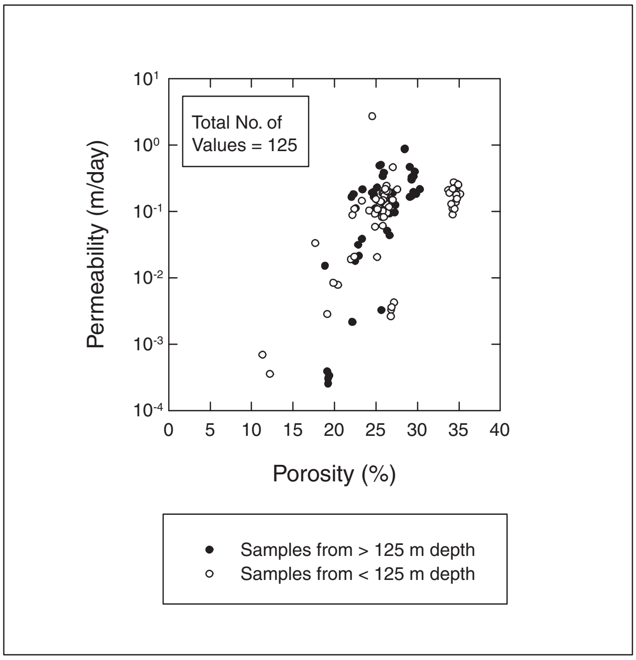


Figure 5.21 Crossplot of permeability against porosity for core samples at different depths in Wealden strata.

between the two formations. In particular there was insufficient evidence to confirm whether or not the Ashdown Formation is most permeable in its top 30 m as indicated by Southern Water Authority (1978).

Porosity data are illustrated in Figures 5.19 and 5.20. Although the overall range is quite wide (from 3.6 to 25.1%), the interquartile range is narrow (22.5 to 25.9%) again suggesting the formation is quite homogeneous. The distribution is very similar to that for the permeability; that is slightly skewed to the left with a large proportion of samples within a narrow range. For the Cuckfield borehole, there is no discernible decline in porosity with depth.

Figure 5.21 shows that there is a positive correlation between porosity and permeability although there is considerable scatter of the data. The correlation appears to be stronger for samples from less than 125 m depth, that is, for the quarry samples.

5.3.3.7 *Pumping test results*

Ashdown Formation

Values of transmissivity range from 1 to 1662 m^2/d, with a geometric mean of 86.3 m^2/d and a fairly narrow interquartile range of 54.2 to 172.2 m^2/d. The data distribution is approximately log-normal, with a slight negative skew (see Figure 5.22); this is reflected in the high median value of 128.0 m^2/d compared to the mean of 86.3 m^2/d. Specific capacities range from 1.9 to 545.0 m^3/d/m, with a geometric mean of 40.7 m^3/d/m, and interquartile range of 14.2 to 109.8 m^3/d/m. The distribution (see Figure 5.23) is again slightly negatively skewed, with the median value (57.0 m^3/d/m) being slightly greater than the geometric mean.

Figure 5.24 illustrates the storage coefficient values for the aquifer. These are wide ranging, from 1.3×10^{-5} to 0.1. To some extent the variability of the values reflects the difference between the confined and unconfined aquifer; however, some large storage coefficients of up to 0.1 have been measured, even where the aquifer is confined.

Figure 5.25 shows the correlation between transmissivity and specific capacity for the Ashdown Formation. There appears to be a moderate correlation, although the coefficient of determination (r^2) is only 0.20.

Table 5.6 Summary of pumping test results for the Ashdown Formation in the Weald.

Ashdown Formation records		
Total number of records	135	—
Number of transmissivity values	74	—
Minimum/maximum transmissivity value (m^2/d)	0.9	1662
Arithmetic/geometric mean of transmissivity (m^2/d)	163	86.3
Median/interquartile range of transmissivity (m^2/d)	128	118
25/75 percentile of transmissivity (m^2/d)	54.2	172
Number of storage coefficient values	29	—
Minimum/maximum storage coefficient value	1.3×10^{-5}	8.5×10^{-2}
Number of specific capacity values	97	—
Minimum/maximum specific capacity value (m^3/d/m)	1.9	545
Arithmetic/geometric mean of specific capacity (m^3/d/m)	91.4	40.7
Median/interquartile range specific capacity (m^3/d/m)	57.0	95.7
25/75 percentile of specific capacity (m^3/d/m)	14.2	110

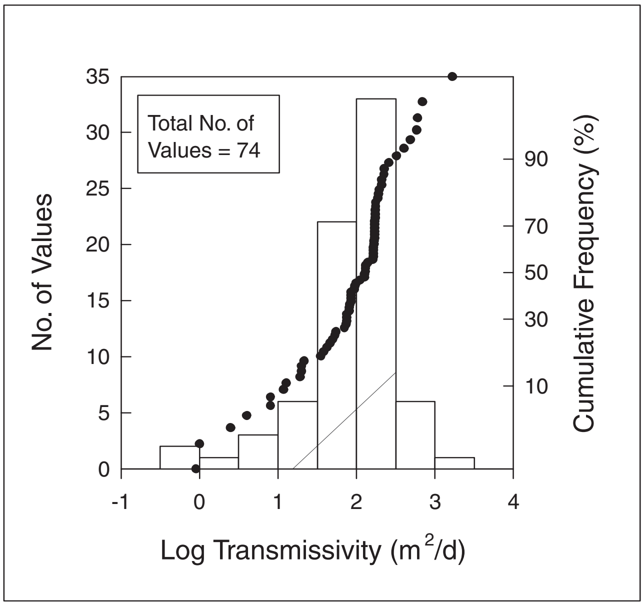


Figure 5.22 Distribution of transmissivity values from pumping tests in the Ashdown Formation.

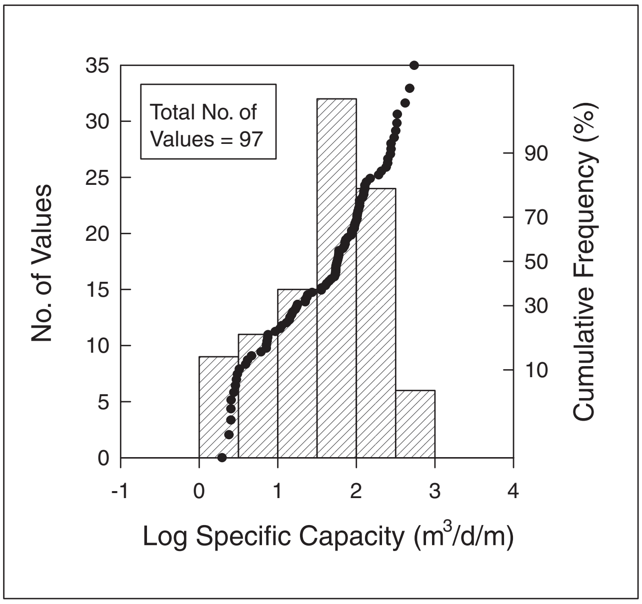


Figure 5.23 Distribution of specific capacity values from pumping tests in the Ashdown Formation.

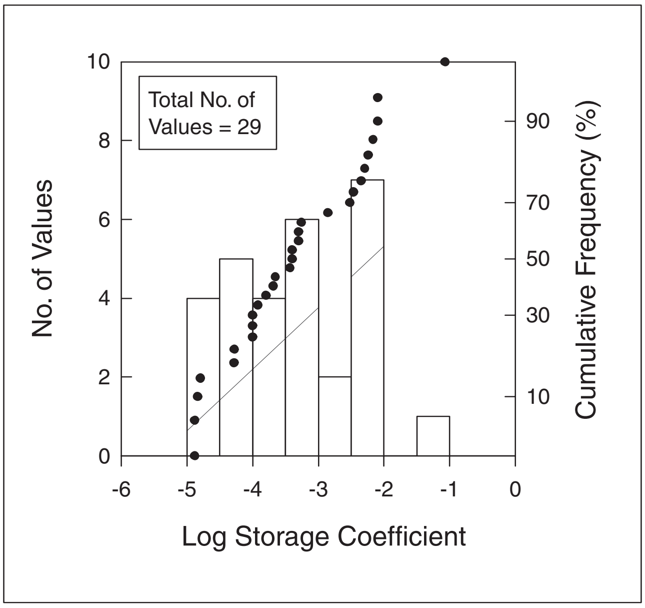


Figure 5.24 Distribution of storage coefficient values from pumping tests in the Ashdown Formation.

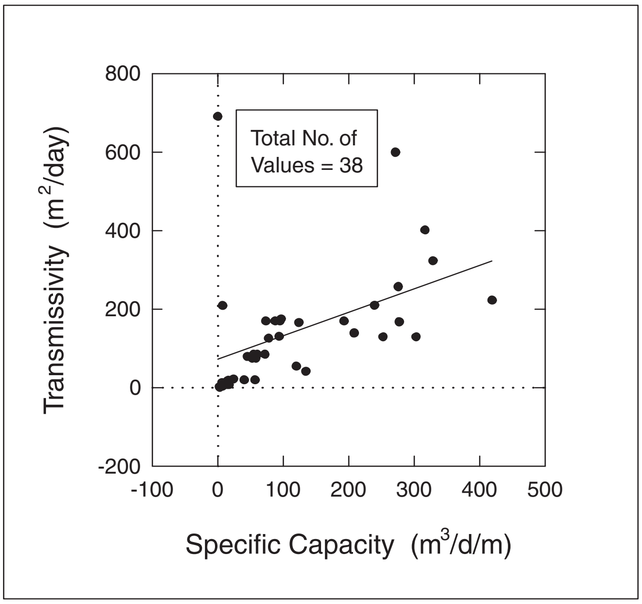


Figure 5.25 Correlation between transmissivity and specific capacity for the Ashdown Formation.

The data collected for this project did not bear out the conclusions drawn by Southern Water Authority (1978), that is, that the confined aquifer had lower transmissivities than the unconfined. The use of all pumping test results instead of the preferred values gave an average (geometric mean) transmissivity value of 72 m^2/d for the confined Ashdown Formation (based on 57 values at 35 sites). The values for the unconfined Ashdown Formation were much higher, with a geometric mean of 296 m^2/d; however, it is likely that these are not representative, as there are only eight values from four sites where the Ashdown Formation is known to be unconfined. Furthermore, the variability in lithology and the effects of structure may cast some doubt on the true meaning of the transmissivity and storage coefficients obtained from pumping tests carried out on these geometrically complex aquifers. If the tests are of too short a duration to allow the cone of depression to intercept barriers, the boundary effects will not be noted, resulting in erroneously high calculated transmissivity values. For example, at Ockham House, Bodiam [TQ 7839 2500], barrier boundary effects due to the lateral variation of the Ashdown Formation are thought to exist, casting some suspicion on the calculated transmissivity value of around 220 m^2/d; a value of around 150 m^2/d is thought to be more reasonable (Southern Water Authority, 1978).

Tunbridge Wells Formation

Values of transmissivity for the Tunbridge Wells Formation are lower than for the Ashdown Formation, ranging from 6.1 to only 39.5 m^2/d, with a geometric mean of 19.0 m^2/d and an interquartile range of 13.8 to 35.4 m^2/d. There were only seven values of transmissivity, and it was not possible

Table 5.7 Summary of pumping test results for the Tunbridge Wells Formation in the Weald.

Tunbridge Wells Formation records		
Total number of records	42	—
Number of transmissivity values	7	—
Minimum/maximum transmissivity value (m^2/d)	6.1	39.5
Arithmetic/geometric mean of transmissivity (m^2/d)	22.0	19.0
Median/interquartile range of transmissivity (m^2/d)	21.1	21.6
25/75 percentile of transmissivity (m^2/d)	13.8	35.4
Number of storage coefficient values	6	—
Minimum/maximum storage coefficient value	4.8×10^{-4}	7.7×10^{-2}
Number of specific capacity values	42	—
Minimum/maximum specific capacity (m^3/d/m)	2.9	511
Arithmetic/geometric mean of specific capacity (m^3/d/m)	53.9	19.2
Median/interquartile range specific capacity (m^3/d/m)	15.6	27.1
25/75 percentile of specific capacity (m^3/d/m)	7.4	34.4

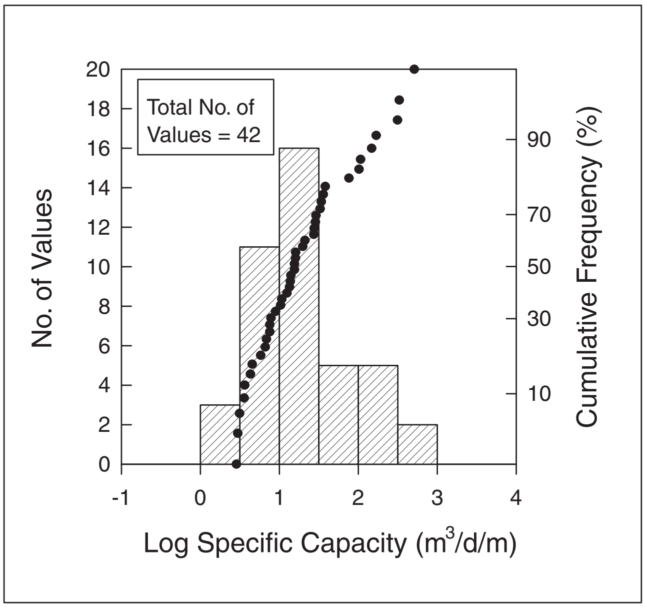


Figure 5.26 Distribution of specific capacity values from pumping tests in the Tunbridge Wells Formation.

to draw any meaningful conclusions about the data distribution. There were rather more specific capacity values (42), their range being similar to that of the Ashdown Formation (2.9 to 511.1 m^3/d/m). However, Figure 5.26 shows the distribution to be slightly positively skewed, and hence the geometric mean of 19.2 m^3/d/m, and interquartile range of 15.6 to 27.1 m^3/d/m, are much lower than for the Ashdown Formation.

The six values of storage coefficient have a fairly narrow range: 4.8×10^{-4} to 7.7×10^{-2}.

5.3.3.8 *Yield data*

Ashdown Formation

Although the Ashdown Formation is the major aquifer of the Hastings Group, yields are nonetheless still variable, due to the lithological and thickness variations in the aquifer, and several boreholes have failed to attain their expected output. Furthermore, the presence of poorly consolidated horizons within the Hastings Group aquifers may cause a reduction in borehole productivities over time due to silting up of the well. Large diameter bores have generally been more successful. For example, at Pembury [TQ 626 425] a 813 mm bore (reducing to 508 mm) yielded 5237 m^3/d on initial test in 1958, dropping to 3055 m^3/d by 1961. At Saint's Hill Pumping Station [TQ 523 414] a 457 mm bore (reducing to 381 mm) yielded 4310 m^3/d for a drawdown of 5.5 m.

Large diameter boreholes situated in valleys are most likely to be successful, especially when sited close to fault zones. An example of this is a 450 mm diameter borehole at Groombridge [TQ 528 364] which overflowed at 305 m^3/d in 1930, and gave a pumped yield of 3490 m^3/d. This site is in a valley, on the edge of a horst of Ashdown Formation, faulted against Tunbridge Wells Formation. Other examples of high yields from large diameter boreholes in valleys include: 4364 m^3/d obtained from a 530 mm diameter bore at the bottom of a shaft at Forest Row [TQ 427 334]; 655 m^3/d from a 450 mm (reducing to 300 mm) bore at Rotherfield [TQ 567 302]; 1090 m^3/d from a 680 mm (reducing to 500 mm) bore at Mayfield [TQ 595 278]; and another at Mayfield [TQ 605 274] of 1637 m^3/d from a borehole 300 mm (reducing to 200 mm) in diameter.

Small diameter boreholes tend to have a disproportionately lower yield, and at some sites, headings have been constructed in order to increase yields. Yields from small diameter boreholes are usually less than 300 m^3/d, although a 200 mm diameter borehole at Bodiam [TQ 7832 2496] yielded 1728 m^3/d.

Tunbridge Wells Formation

Yields from the Tunbridge Wells Formation are generally less than 400 m^3/d, and often less than 100 m^3/d, although significantly higher yields have been obtained on occasion. At the former Adam's Hole Pumping Station in Herstmonceux [TQ 6148 1138], a borehole 26.5 m deep and 305 mm in diameter yielded 2046 m^3/d on test. The largest recorded yield from the Tunbridge Wells Formation is from the former Whitesbridge Pumping Station in Horsham, where a borehole of 762 mm diameter (reducing to 610 mm) yielded 5919 m^3/d from the Upper Tunbridge Wells Formation for 11.6 m drawdown during a 35 hour test.

It has been suggested that larger yields are generally obtained from the Lower Tunbridge Wells Formation, especially the Ardingly Sandstone, than from the Upper Tunbridge Wells Formation (Dines et al., 1969; Gallois and Worssam, 1993). However, the above example indicates that this is not always the case.

As groundwater flow within the Tunbridge Wells Formation is both intergranular and through joints, well yields tend to be variable and combined with the problem of siltation it has sometimes proved necessary to excavate adits to obtain and maintain productive capacity.

Combined Ashdown and Tunbridge Wells formations

There are very few data available regarding the properties of the combined Ashdown and Tunbridge Wells formations. At New Wharf Road Pumping Station, Tunbridge [TQ 588 464] the Ashdown Formation and Lower Tunbridge Wells Formation together yielded 2620 m^3/d. Surprisingly, bores attempting to penetrate all three aquifers (Ashdown, Lower Tunbridge Wells and Upper Tunbridge Wells formations) are reported to be generally unsuccessful, either due to insufficient yield or rapid siltation.

5.3.3.9 *Controls on permeability and transmissivity*

The main controls on permeability and transmissivity of the aquifers of the Hastings Group are lithology and degree of cementation, both of which show great variation. Furthermore, faults and folding add a structural complexity. Thus prediction of aquifer properties is difficult.

The study of the Rother Basin by Southern Water Authority (1978) indicated that the top 30 m of the Ashdown Formation was the most permeable part of the formation. Transmissivity should therefore be higher in boreholes where this part of the Ashdown Formation is saturated, i.e., where the Ashdown Formation is confined by the overlying clay, than in boreholes penetrating unconfined Ashdown Formation when the top part may be absent or unsaturated. However, as discussed in Section 5.3.3.7, the pumping test data collected for the present study do not corroborate this conclusion, as the average transmissivity value for the unconfined Ashdown Formation is higher than that for the confined Ashdown Formation.

5.3.3.10 *Effect of structures*

As described above, the general structure controls the overall flow of groundwater in the Weald: that is a pericline with the strata dipping away from the centre. However, the simple periclinal arrangement is greatly complicated by a series of minor folds, roughly parallel to the main axis of the Weald. A characteristic of these folds is that the anticlines are asymmetrical, having steeply dipping northern and gently sloping southern limbs. Groundwater tends to flow in the direction of dip: towards the axes of synclines, and away from the axes of anticlines.

Faulting also has a major effect on the hydrogeological regime. Strike faulting which throws the Wadhurst Clay Formation against the Ashdown Formation can cause partial or complete reduction in the hydraulic continuity between adjacent blocks of Ashdown Formation. For example, if faulting causes a juxtaposition of the Wadhurst Clay Formation against the Ashdown or Tunbridge Wells formations, the fault is likely to act as a barrier to groundwater flow and compartmentalisation of the aquifer may occur. A possible example of this is shown by a pumping test analysis at Powdermill [TQ 7431 1496] which identified a barrier to groundwater flow ascribed to faulting.

However, it is uncertain whether faults always act as boundaries. Faulting may also juxtapose the Ashdown and Tunbridge Wells formations either against themselves or against each other, in which case groundwater flow may still occur, although possibly to a lesser extent. For example, Forewood Pumping Station [TQ 746 132] draws water from the Ashdown Formation which forms an inlier of limited outcrop. The calculated average annual recharge over this area does not meet the abstraction, and so it appears that the bulk of Forewood's water is derived from sources other than recharge to the inlier. The possibilities include movement of groundwater from adjacent fault blocks, although it could alternatively be accounted for by a leaky aquifer condition. Also, at Chase Wood, where faults exist close to the borehole, a short pumping test did not reveal the presence of barrier boundaries. It seems that in both cases, nearby faults are not acting as a complete barrier to groundwater movement, although it is possible that the pumping tests were not long enough to demonstrate the barrier effect. A local effect that can also occur is enhancement of permeability along the plane of faulting itself, such that even though regionally the fault creates a barrier boundary, the fault itself is transmissive.

In some parts of the Weald the general effect of the faulting has been to break up the beds in such a way that erosion has left outliers of water-bearing beds resting on impermeable older formations. These outliers act as isolated reservoirs, and usually have small springs at their margins, which may sometimes be used for small domestic supplies. Faults may also enhance the ease of groundwater recharge and abstraction because of the fracturing and general disturbance. This may be especially the case along valley sides where cambering has opened up vertical tension joints (see Figure 5.16).

5.4 THE LOWER CRETACEOUS/UPPER JURASSIC OF NORFOLK

5.4.1 Introduction

There are three separate Lower Cretaceous/Upper Jurassic minor aquifers present in western Norfolk, the Sandringham Sands Formation, the Roach Formation and the Carstone Formation (see Table 5.1).

The Sandringham Sands Formation of north-west Norfolk represents the change at the end of the Jurassic period from uniform quiet water deposition, to more turbulent, near-shore conditions in response to developing earth movements. The formation comprises around 50 m of arenaceous sediments above the Kimmeridge Clay and is the main Lower Cretaceous aquifer in the area, although the overlying Dersingham Beds, Roach Formation and Carstone Formation may provide local supplies. These latter formations are dealt with briefly, because there are few aquifer properties data for them. It is possible that they may occasionally have been misclassified as Sandringham Sands in boreholes, or may be in hydraulic continuity with the Sandringham Sands Formation (see Section 5.4.3.6). There is a general stratigraphic dip of around 0.5° to the east, and as the drainage direction is from east to west, the rivers cut across the strike, and flow into The Wash.

5.4.2 Geology and stratigraphy

5.4.2.1 *Extent of aquifer group, stratigraphy and lithology*

The Sandringham Sands Formation forms a narrow outcrop in north Norfolk along the eastern margin of The Wash from near Hunstanton in the north to Denver in the south (see Figure 5.27). The formation also extends northwards across The Wash into south Lincolnshire where it is known as the

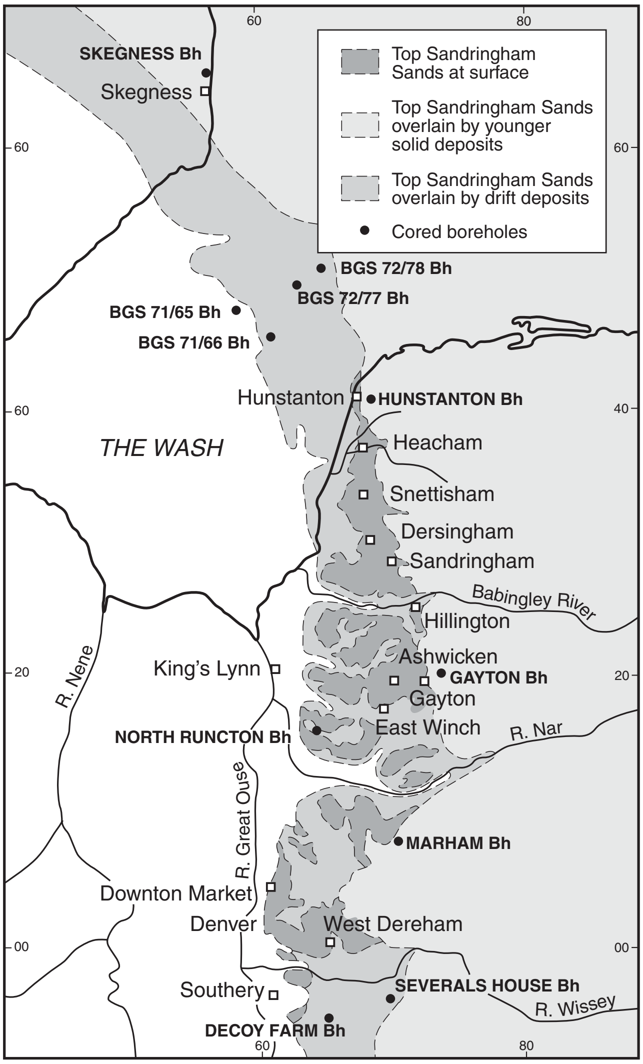


Figure 5.27 Outcrop of Lower Cretaceous/uppermost Jurassic rocks in Norfolk (from Gallois, 1994).

Spilsby Sandstone. The term 'Lower Greensand' has been used to describe the Carstone Formation, Dersingham Beds, and Sandringham Sands Formation, although this is incorrect as only part of the Carstone appears to be equivalent to the Lower Greensand Group of southern England (Jackson, 1983).

The Sandringham Sands Formation rests unconformably on the Jurassic Kimmeridge Clay. The formation is of quite limited extent, gradually thinning to the south, and being progressively overstepped southwards by the Carstone Formation, until completely cut out at Southery (Dijkstal, 1992). In the north it is overlain conformably by the Dersingham Beds, but to the south the Carstone oversteps onto progressively older members of the formation (Figure 5.28). Pleistocene deposits overlay much of the outcrop. The formation comprises up to about 50 m of predominantly arenaceous sediments and has been divided into several distinctive members (see Table 5.1).

The basal member of the Sandringham Sands Formation is the Roxham Beds, some 3 to 6 m of poorly consolidated grey and yellowish green, locally glauconitic sands with disseminated pyrite and, at some levels, pyritic nodules.

The lowermost bed, which may be up to 1.5 m thick, comprises a calcite-cemented, fine-grained, grey sandstone crowded with pebbles of black chert and black phosphate. This basal sandstone is very persistent throughout the outcrop and forms a marked feature and spring-line at outcrop. The common occurrence of large boulders of the sandstone in the overlying Quaternary till suggests that it may locally be present as concretionary masses rather than a tabular bed. It forms a prominent seismic reflector beneath The Wash. A similar seismic reflector, a phosphatic pebble bed, occurs at the base of the Spilsby Sandstone in Lincolnshire. Temporary sections suggest that the Roxham Beds remain lithologically uniform.

The Roxham Beds have been mapped from their most northerly occurrence, on the banks of the Babingley River [TF 652 255] to their disappearance beneath Methwold Fens near Ely. Northwards erosion has cut out the Roxham Beds at the base of the overlying Mintlyn Beds.

The overlying Runcton Beds, consisting of up to 1.5 m of dark green, highly glauconitic sands with phosphatic pebble beds, can be traced as far north as about Hunstanton. To the south (West Dereham) and east (Gayton and Marham boreholes, see Figure 5.27) the formation is absent; this is due to overstep by the overlying Mintlyn Beds.

The Mintlyn Beds have their maximum thickness of about 20 m around King's Lynn, thinning to about 11 m near Hunstanton. The progressive southerly overstep of the Carstone Formation across the Sandringham Sands Formation brings the Carstone to rest on the Mintlyn Beds at Denver [TF 624 014]. The Carstone then cuts out the Mintlyn Beds entirely between there and Southery in south-west Norfolk. Their northerly and easterly limits are not well defined. A thin representative of the Mintlyn Beds, overlain by the Claxby Beds, was proved in the central Wash area. The base of the beds in Norfolk is equivalent to the mid-Spilsby nodule bed in Lincolnshire.

The Mintlyn Beds consist of grey, greyish green and green glauconitic sands and clayey sands with thin beds and nodular lines of clay ironstone (sideritic mudstone). They may have laminae, mostly less than 15 cm thick, of green glauconitic clay. Phosphatic pebble beds occur at several horizons. The high iron content and low permeability of the Mintlyn Beds cause them to weather to poorly drained, dirty orange-brown sand with much secondary limonite, commonly forming an iron pan.

The overlying Leziate Beds have a narrow north-south outcrop that extends from Snettisham in the north to near West Dereham in the south. To the north of Snettisham the Leziate Beds have been proved in boreholes; at Hunstanton 20 m are present but the formation thickens southwards, where in the Leziate-Middleton area some 30 m are present. Buckley et al. (1989) report that the beds are 34 m thick at Hillington. The beds thin again south of Gayton as a result of overstep of the Carstone Formation, and disappear south of Marham.

The Leziate Beds comprise loose, fine-grained, cross-bedded quartz sands, yellow, green, orange-brown, or red in places, but mostly clean grey or white, with subordinate bands of silt and clay. Locally the sands are lithified to form a friable sandstone. Ferruginous cements are common, as are pyritic nodules which, above the water table, become oxidised to form limonitic concretions, geodes or ferruginous stains. The sands are mostly fine-grained, although locally include medium- and coarse-grained beds. The Leziate Beds have been dug extensively for glass and foundry sands. When traced northwards into Lincolnshire, the Leziate Beds pass laterally into the argillaceous Claxby Beds.

Overlying, and in hydraulic continuity with, the upper Leziate Beds are the Dersingham Beds. These comprise a

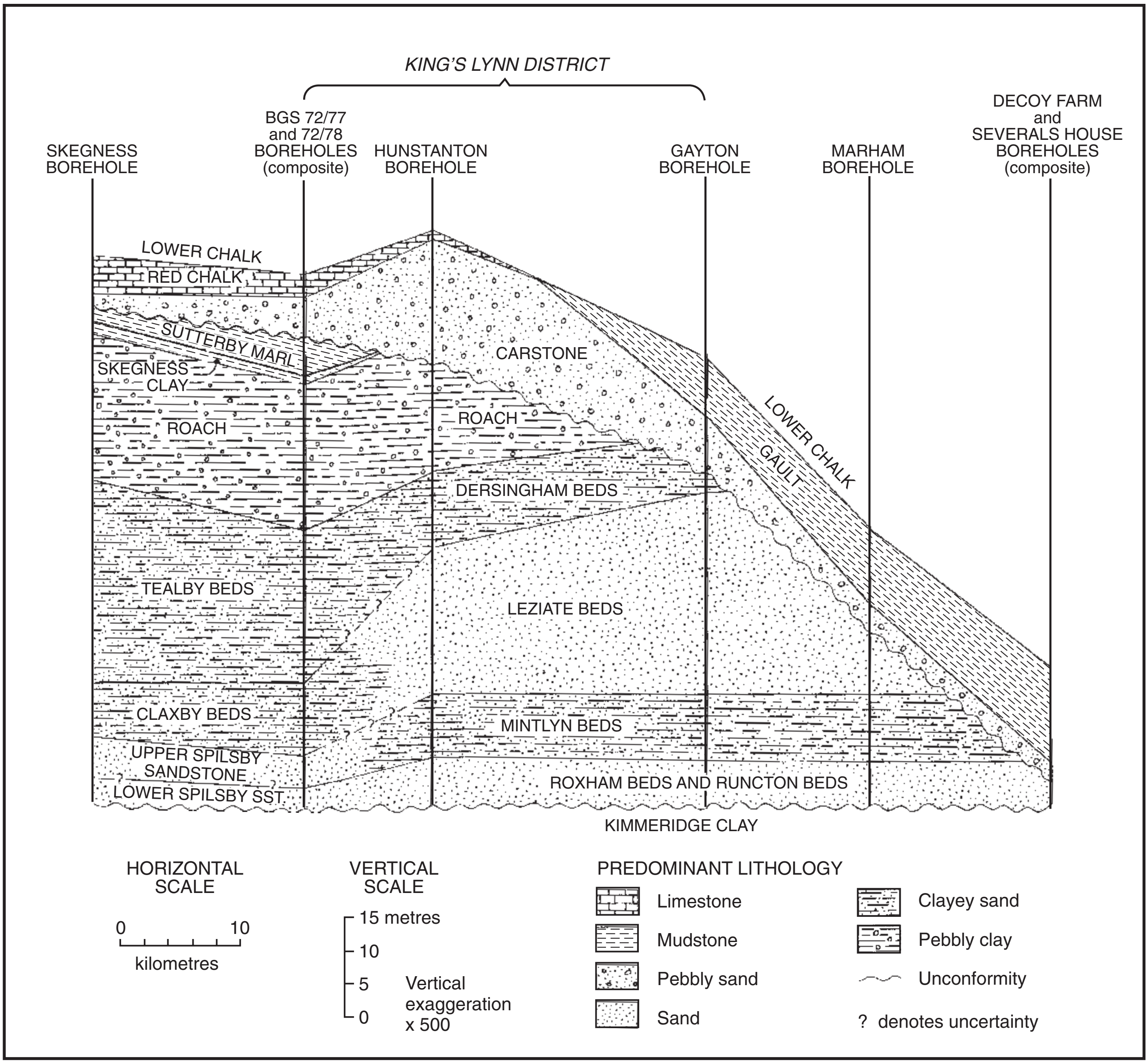


Figure 5.28 Cross-section along strike of Lower Cretaceous/uppermost Jurassic rocks north and south of The Wash (from Gallois, 1994).

laterally variable rhythmic sequence of thinly bedded fine-grained sands, ferruginous sandstones, silts and clays. The upper part of the sequence contains a laterally persistent clay layer known as the Snettisham Clay, which extends from East Winch in the south to Hunstanton in the north (Dijkstal, 1992; Wright, 1992). Figure 5.29 illustrates the sequence at Dersingham. The beds are highly ferruginous in places with development of ironstone. At outcrop the beds undergo a broad lithological change from predominantly sands in the south to a mixture of sands and clays in the north; they pass laterally into the Tealby Beds of Lincolnshire.

The Dersingham Beds form an almost continuous, and largely drift-free, outcrop from Heacham to the Babingley River in north Norfolk. Southwards from the Babingley River they crop out, commonly from beneath extensive drift deposits, as far as East Winch. The extent of their subcrop is poorly known. The formation was proved in the Gayton and Hunstanton area and might be expected to occur beneath much of north-west Norfolk. Their maximum thickness is about 16 m in the Dersingham area. The basal ferruginous sandstones of the beds cap a steep scarp between The Wash at Heacham and Kings Lynn, forming one of the most prominent features in north Norfolk. The contrast in permeability and induration between the Leziate Beds and basal Dersingham Beds gives rise to a weak springline.

The Dersingham Beds are overlain by the Snettisham Clay and the Roach Formation, but in the south the Carstone Formation oversteps the Roach to directly overlie the Dersingham Beds (Figure 5.27).

Overlying the Dersingham Beds in Norfolk is the Roach Formation. In Norfolk and much of Lincolnshire this, in turn, is overlain by the Carstone Formation but in south Lincolnshire and the northern Wash area, the Sutterby Marl and Skegness Clay intervene (Figure 5.27). The Roach Formation has a very limited extent in Norfolk, stretching from north of Heacham to Hunstanton (Wright, 1992);

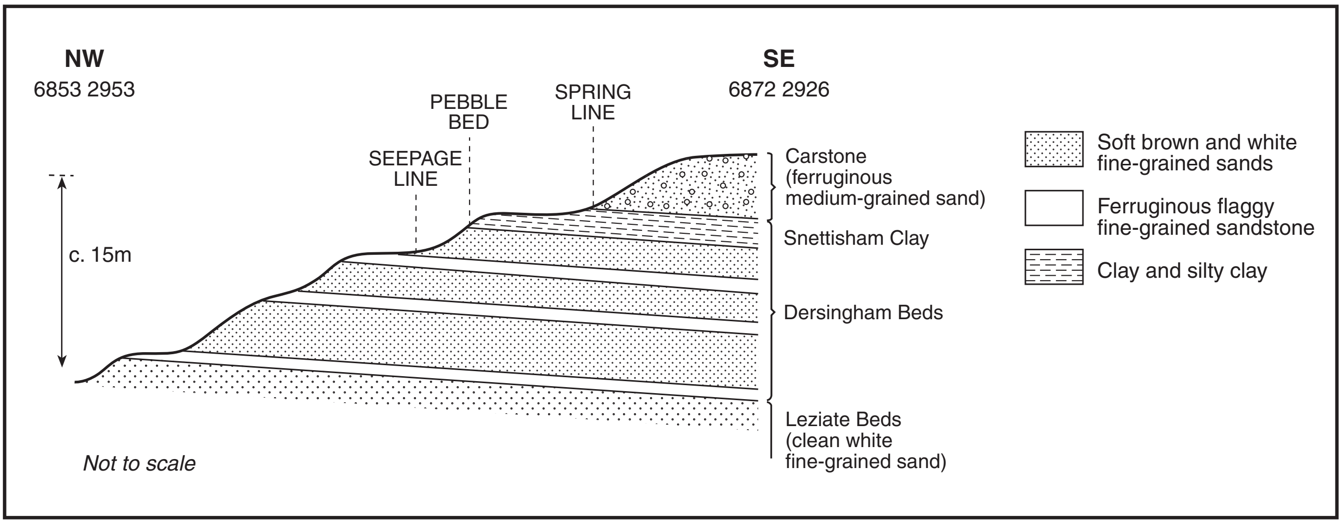


Figure 5.29 Section through Lower Cretaceous strata at Dersingham showing the disposition of Lower Cretaceous aquifers (from Gallois, 1994).

Quaternary deposits cover most of its outcrop. The Roach Formation is unknown to the south of the Ringstead Downs valley [TF 678 392], where it is overstepped by the Carstone Formation. In Norfolk the base of the formation is taken as a minor erosion surface that separates the mainly oolitic and pebbly clays of the Roach Formation from the predominantly argillaceous, sparsely pebbly, Dersingham Beds. About 12 m appear to be present at Hunstanton.

The term 'Roach' was introduced in the latter part of the last century, to describe a group of oolitic and pebbly sandy clays in the upper part of the Lincolnshire Lower Cretaceous sequence. The beds assigned to the Roach Formation in the Hunstanton and Skegness areas consist of a complex rhythmic sequence of interbedded lithologies made up of varying amounts of clay, 'chamosite' mud, 'chamosite' ooliths, quartz sand and small pebbles of quartz and ironstone. Calcitic and ferruginous cementation are common. The Roach sequence at Hunstanton continues the fining-upward rhythmic succession of the Dersingham Beds. However, in contrast to the Dersingham Beds cyclic sequences, those of the Roach Formation are commonly thin. Most of the base members appear to be erosive and probably give rise to rapid lateral changes that make correlation of the Roach sequences across the mouth of The Wash difficult and uncertain. These beds underlie much of the lowermost part of the beach at Hunstanton to the north of the pier, but are overlain by beach gravel and sand.

The overlying Carstone Formation (maximum thickness 12 m) oversteps the earlier Cretaceous beds at either end of its outcrop where it rests on Jurassic sediments. It is generally a medium to coarse-grained, pebbly, quartz sand, with a brown stain due to limonitic cement (Rawson, 1992); it becomes more silty south of Sandringham. Distinct pebble beds occur, and the base may become conglomeratic towards the margins of the outcrop. Some of the sediments may have been reworked from earlier Lower Cretaceous deposits. The upper beds are characteristically well cemented, and the stone is used locally as a building material. In an area north of the River Nar, the lithology of the Carstone Formation changes, becoming a harder, denser, iron-rich sandstone, which is nodular in appearance (Dijkstal, 1992). This is locally called Ragstone, and the change has been attributed possibly to iron oxidation and precipitation from groundwater.

The Carstone Formation extends from the northern margin of the East Anglian Massif to the southern part of the Market Weighton high with scattered patches further north (Rawson, 1992). It grades up into the Hunstanton Formation (formally Red Chalk) over much of the shelf, but at its southern extent is overlain by the Gault Clay Formation. The formation is thickest in the north, attaining 21.3 m at Holkham, and thins southwards to 4 m at Mundford, and 0.9 m south of Stoke Ferry (IGS, 1976). It dies out eastwards.

5.4.2.2 *Depositional history*

The Lower Cretaceous sediments, both north and south of The Wash, accumulated in the Spilsby Basin, between the Market Weighton High and the East Anglian Massif (see Figure 5.1). Within this basin, in south Humberside and north Norfolk, a thin series (approximately 50 m) of shallow marine sediments was laid down in a near-shore environment (Rawson, 1992). The western limit of the basin is though to have been possibly only a few kilometres west of the present outcrop. Between the two areas was a broad intervening area of offshore, inner- to mid-shelf sedimentation. At the start of the Albian, an important transgression marked the beginning of a new and more widespread phase of sedimentation resulting in deposition of the Carstone Formation.

5.4.2.3 *Structures*

There are no major structures affecting the Lower Cretaceous/ Upper Jurassic sediments of north Norfolk. The beds dip gently to the east at an angle of approximately 0.5°.

5.4.3 Hydrogeology

5.4.3.1 *Introduction*

The Lower Cretaceous/Upper Jurassic aquifer system of north Norfolk is complex due to the varying inter-relationships between different formations and beds. Previously the strata have been considered to be a single aquifer, although it is now recognised that a multi-layered aquifer system exists (see Section 5.4.3.4).

In general, there has been limited exploitation of the Lower Cretaceous sands for water, and the resources and hydrogeology of the Sandringham Sands aquifer in particular were little studied before the construction of the wellfield for the Norfolk Blending Scheme (see below). Difficulties with running sands, especially in the Sandringham Sands aquifer have been reported as a constraint limiting the use of the aquifer, although large yields have been achieved in properly constructed boreholes. For example, 4000 m^3/d was recorded from the combined aquifer at Congham Heath [TF 71 23], and 4500 m^3/d from the Sandringham Sands Formation at Hillington [TF 71 25] (IGS, 1976). Abstraction is a major source of groundwater discharge from the Lower Cretaceous aquifers, especially in the catchments of the Babingley and Gaywood rivers.

Artesian flow was recorded from the aquifer near Stoke Ferry [TF 70 00] and Lowestoft (IGS, 1976). At the latter, the formation was reached at a depth of 480 m below OD, and yielded highly mineralised water.

Several buried valleys exist in the area, some of which may cut through overlying deposits to the Cretaceous sandstones, or deeper. For example, the Babingley buried valley cuts through the Lower Cretaceous sands to the Kimmeridge Clay. It has been suggested that loss of river flow may be coincident with the presence of buried glacial valleys, with the 'lost' water using the valley as a channel in which to flow (Wright, 1992).

5.4.3.2 *Previous studies*

The majority of previous work has been carried out in connection with the Northwest Norfolk Groundwater Blending Scheme. This scheme was initiated because many unconfined Chalk groundwater sources in Norfolk had exhibited high or rising nitrate concentrations over a number of years. To reduce nitrate in water used for public supply to an acceptable level, one option considered was blending of the chalk water with low nitrate water from alternative sources. As a result, a feasibility study in the late 1980s investigated blending of Sandringham Sands groundwater with that from the Chalk, and a wellfield tapping the Sandringham Sands Formation was constructed (Dijkstal, 1992). An initial observation network was installed in 1982/1983, and was improved by the National Rivers Authority in the early 1990s to monitor the groundwater resource during the ten year license period of the wellfield (Dijkstal, 1992). The data from these boreholes were used to help evaluate flow directions and hydraulic gradients.

5.4.3.3 *Groundwater flow and recharge*

Prior to the construction and monitoring of the National Rivers Authority observation network, little information was available concerning the flow directions and hydraulic gradients within the Sandringham Sands aquifer, and many of the following comments have been drawn from its results. To the north of the area of the Norfolk Groundwater Blending Scheme, groundwater flow is towards The Wash. Beneath Hillington itself, there is a groundwater mound (Dijkstal, 1992; McKelvey, 1993). Dijkstal suggested this was possibly a recharge mound, although the aquifer is confined in this area. Alternatively McKelvey (1993) believed high groundwater levels here might be supported by flow from the north. Other suggestions are that this could be due to unrepresentative data, or as a result of leakage from the overlying Chalk. South of Grimston and the River Gaywood, groundwater flow is generally southerly; from the outcrop, it is in a south-south-east direction, and from the confined aquifer, in a south-south-west direction (Dijkstal, 1992). It appears to converge in an area north of the River Nar, where the Carstone lithology changes locally to the hard, dense sandstone called Ragstone (see Section 5.4.2.1), a change which has been tentatively attributed to iron oxidation and precipitation from groundwater (Dijkstal, 1992). Both the Carstone and Sandringham Sands aquifers appear to discharge to the River Nar (McKelvey, 1993). South of the River Nar, the groundwater contours indicate northward flow towards the river. The regional hydraulic gradient varies between 0.002 south of Grimston and 0.00025 in the East Winch area (Dijkstal, 1992).

Recharge to the Lower Cretaceous aquifers occurs at outcrop, and possibly to a lesser degree from rivers. It may also occur as leakage where the Gault facies changes to Red Chalk towards the north of the area, although where present, the Gault Clay Formation is assumed to prevent significant vertical flow between the two aquifer systems (Dijkstal, 1992). Influent seepage from streams is seen as an important factor in aquifer recharge to both the Dersingham Beds and Sandringham Sands Formation, although it is poorly understood, with some conflicting evidence as to whether streams are actually effluent or influent. For example, several streams are seen to decrease in flow or disappear when passing across their outcrop, an example being the River Babingley (Wright, 1992). In contrast, from flow gauging work carried out by the National Rivers Authority, there was evidence that the River Babingley receives approximately 29% of its baseflow from the combined Carstone, Dersingham Beds, and Sandringham Sands aquifers (Dijkstal, 1992). There is further evidence of effluent seepage in streamflow over the Carstone Formation, for example where the River Babingley crosses the Carstone a red colouration indicates seepage of high iron water from the Carstone into the stream (Wright, 1992). It is quite possible that the relationship between surface and groundwater varies according to potentiometric level elevation.

The presence of glacial till has the potential to cause increased surface run-off, and therefore reduce infiltration. However, the exact composition of the till would determine the extent to which this occurs.

Springs and seepages occur in various areas: for example at the base of the Carstone Formation at the intersection with the Snettisham Clay, at the junction of the Leziate Beds and basal Dersingham Beds, and at the base of the Leziate Beds adjacent to the Mintlyn Beds (Wright, 1992). Wright (1992) observed that many Carstone springs were dry or had much less flow in 1992 than in the period when they were mapped by Gallois between 1965 and 1971, and concluded that water levels had declined. However this should not necessarily be taken as an indication of long term lowering of groundwater levels in the aquifer, as the latter survey was carried out towards the end of an extended period of groundwater drought in the area.

5.4.3.4 *Nature and extent of confinement*

The extent and nature of confinement of the Lower Cretaceous aquifers is variable across the north Norfolk area. Previously the strata had been considered to be a single aquifer, although it is now recognised that there is a multi-aquifer system (Wright, 1992). This is illustrated in Figure 5.30 (from Wright, 1992) which shows the simplified succession between Hunstanton in the north and Marham in the south, highlighting the array of potential hydraulic relationships between the different sand units.

The Kimmeridge Clay defines the base of the Lower Cretaceous/Upper Jurassic aquifer system. The Sandringham

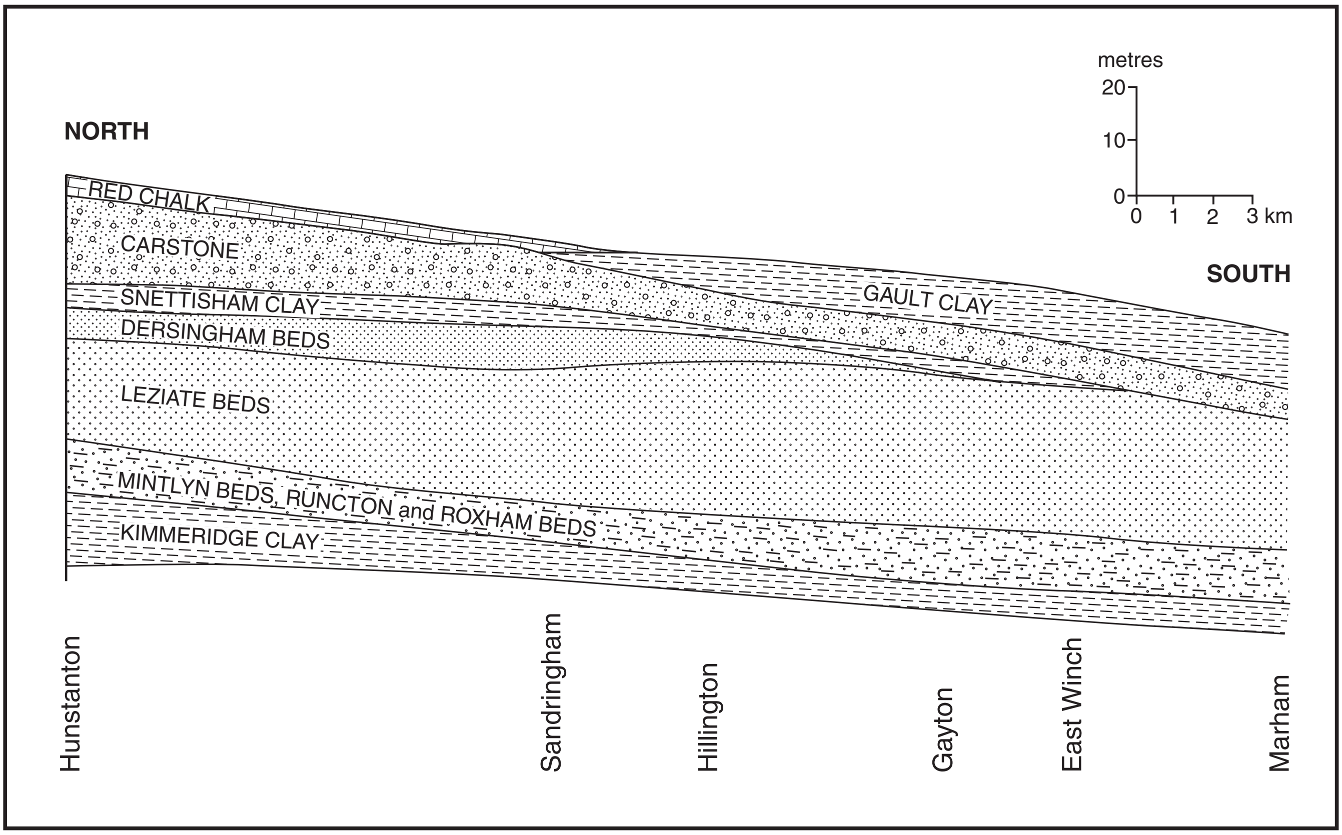


Figure 5.30 Geological section illustrating the varying contact relationship between Lower Cretaceous/uppermost Jurassic minor aquifers in north Norfolk (from Wright, 1992).

Sands Formation above may be confined by the Dersingham Beds in the north of the area, where these are highly argillaceous (Wright, 1992). Further south, the sand content increases, and the beds are instead in hydraulic continuity with the Sandringham Sands Formation. South of Gayton, borehole logs indicate the presence of a band of clay within the Leziate Beds themselves. This is thought to divide the Sandringham Sands Formation into two units, and may result in reduced yields in this area (Dijkstal, 1992).

The Snettisham Clay separates the Carstone Formation and Sandringham Sands Formation/Dersingham Beds over much of the area north of East Winch. In the Congham area, the Dersingham Beds are overstepped by the Snettisham Clay, which then separates the Carstone Formation and Sandringham Sands Formation. At East Winch, the Snettisham Clay pinches out, and the Carstone directly overlies the Leziate Beds, with which it is in hydraulic continuity (Wright, 1992).

The Gault Clay Formation acts as a confining layer in the south, separating the Lower Chalk and the Carstone aquifer (Dijkstal, 1992), and preventing any substantial vertical flow of Chalk water down into the Carstone and/or the Sandringham Sands formations. The hydraulic discontinuity has been proved by test pumping (Dijkstal, 1992). The Gault Clay Formation is replaced by Red Chalk, now known as the Hunstanton Formation (Rawson, 1992), to the north, and the degree of confinement is reduced such that the Chalk and Carstone Formation are considered to be in hydraulic connection (Wright, 1992). The exact zone of the transition is unknown.

Groundwater level measurements have shown head differences do exist between the Chalk, Carstone Formation and Leziate Beds, and the potential exists for vertical leakage (Dijkstal, 1992; McKelvey, 1993). However, there is no evidence from groundwater chemistry that this does occur, nor does the aquifer response to abstraction suggest it occurs to any extent. The potential for leakage must be greatest where the Gault Clay Formation or Snettisham Clay are relatively thin or absent, that is, north of Hillington for the Gault, and south of Hillington for the Snettisham Clay.

Glacial till and other superficial deposits may also act as confining horizons in localised areas (Wright, 1992).

5.4.3.5 *Aquifer properties*

Previous work (McKelvey, 1993) has shown that the highest values of transmissivity for the Sandringham Sands aquifer occur around the Hillington area, where they are generally in the range 240 to 300 m^2/d. McKelvey (1993) noted that particularly low figures in some areas could be a result either of the borehole penetrating thick, low permeability drift, or of increased clay in the aquifer. McKelvey (1993) also described decreasing values to the north and south, and attributed the latter to thinning of the aquifer in that direction.

From the data collection exercise carried out for this project, pumping test data were apparently only available for the Sandringham Sands aquifer; the data were sometimes specific to the Leziate Beds. Where the Sandringham Sands aquifer is in hydraulic continuity with the Dersingham Beds (north of Gayton) or with the Carstone Formation (south of East Winch), the values probably reflect the combined aquifer. There is also the possibility, as in Lincolnshire, that boreholes penetrating only the upper aquifers (i.e. the Carstone Formation, Roach Formation or Dersingham Beds) have been misclassified. There were 32 analyses of transmissivity, but only six of storage coefficient. Twenty seven values of specific capacity were available (see Table 5.8 and Figures 5.31 and 5.32).

Table 5.8 Summary of pumping test results for the Sandringham Sands Formation.

Sandringham Sands Formation records		
Total number of records	35	—
Number of transmissivity values	32	—
Minimum/maximum transmissivity value (m^2/d)	8.5	2325
Arithmetic/geometric mean of transmissivity (m^2/d)	288	120
Median/interquartile range of transmissivity (m^2/d)	145	203
25/75 percentile of transmissivity (m^2/d)	52.3	255
Number of storage coefficient values	6	—
Minimum/maximum storage coefficient value	1.4×10^{-4}	4.7×10^{-4}
Number of specific capacity values	27	—
Minimum/maximum specific capacity value ($m^3/d/m$)	3.5	421
Arithmetic/geometric mean of specific capacity ($m^3/d/m$)	93.7	45.0
Median/interquartile range specific capacity ($m^3/d/m$)	56.2	76.4
25/75 percentile of specific capacity ($m^3/d/m$)	24.5	101

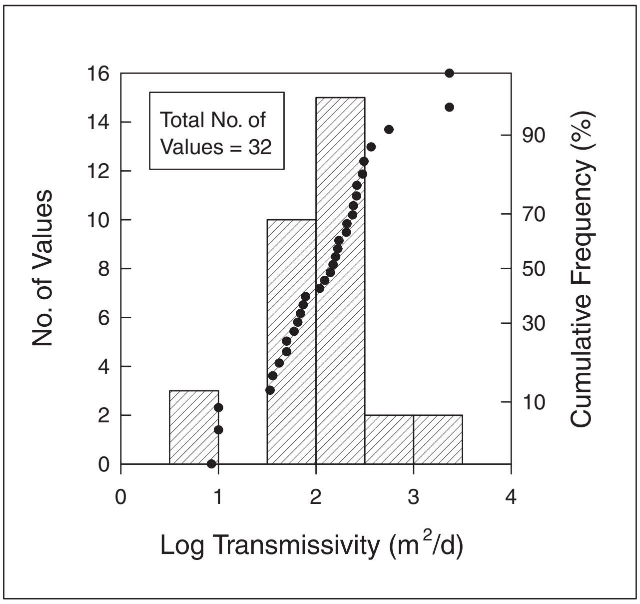


Figure 5.31 Distribution of transmissivity values from pumping tests in the Lower Cretaceous sands of Norfolk.

5.4.3.6 *Pumping test results*

Transmissivity shows a log-normal distribution, ranging from 8.5 to 2325 m^2/d, with an interquartile range of 52 to 255 m^2/d, and a geometric mean of 120 m^2/d (see Table 5.8 and Figure 5.31). Storage coefficients range from 1.4×10^{-4} to 4.7×10^{-4}; with only six analyses, it was not possible to obtain a meaningful mean or median value. The values suggest mainly confined conditions at the pumping test sites. There were 27 specific capacity values, ranging from 3.5 to 421 $m^3/d/m$, with an interquartile range of 25 to 101 $m^3/d/m$, and a mean of 45 $m^3/d/m$ (see Table 5.8 and Figure 5.32).

There is a positive, moderately good correlation between specific capacity and transmissivity, with a value of r^2 of 0.68 (see Figure 5.33). Thus for areas where few pumping test results are available, specific capacity data could provide an indication of transmissivity of the aquifer. However, as specific capacity depends on numerous other factors, such as borehole diameter, well efficiency, position of the pump intake, duration of pumping, and, taking into account the limited number of data points, this relationship should be treated with caution.

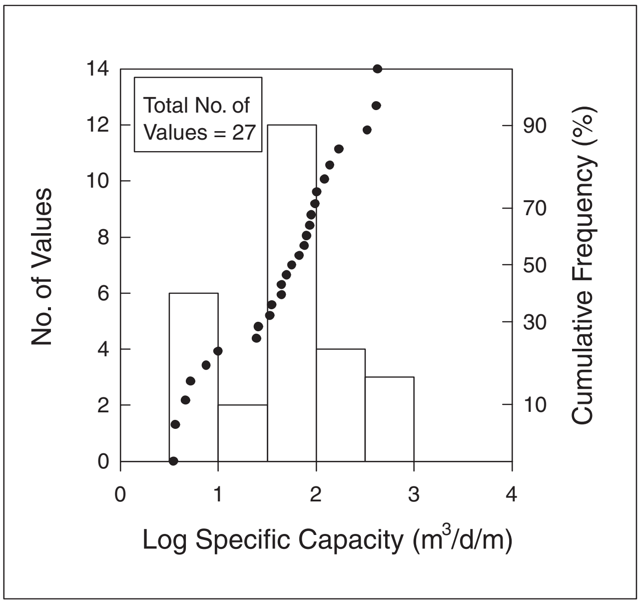


Figure 5.32 Distribution of specific capacity values from pumping tests in the Lower Cretaceous sands of Norfolk.

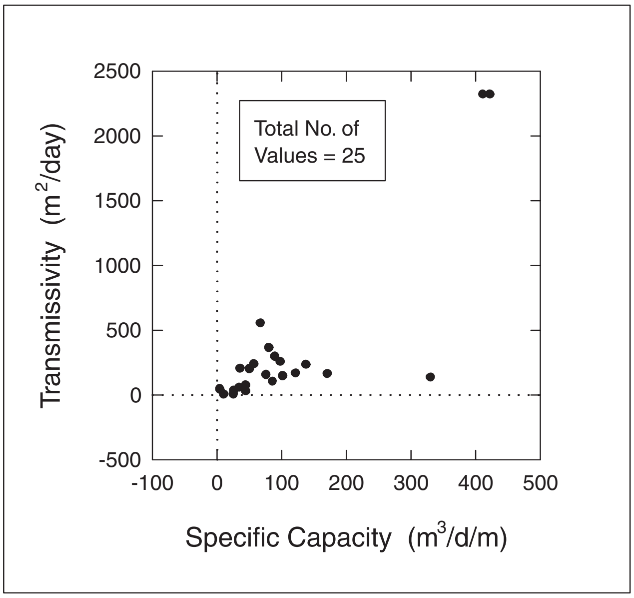


Figure 5.33 Correlation between transmissivity and specific capacity for the Lower Cretaceous sands of Norfolk.

5.4.3.7 *Yield data*

Monkhouse and Richards (1982) state that yields are usually in the order of 2700 m^3/d, although yields up to 10 000 m^3/d have been recorded. IGS (1976) also reported yields of 4000 m^3/d at Congham Heath (combined aquifer), and 4500 m^3/d at Hillington (Sandringham Sands Formation). From the data collected for this project, yields varied between 45 and 2574 m^3/d, substantially lower than the earlier estimates.

5.4.3.8 *Controls on permeability and transmissivity*

Grain size distribution is likely to be one of the main controls on aquifer properties. For example, the most productive horizon of the Sandringham Sands Formation is the Leziate Beds. The upper part of that formation is observed to be usually more productive than the lower part due to the coarser grain size. The lower unit becomes progressively finer grained at depth with an increased silt content.

The presence of a variety of drift deposits may also have resulted in variations in aquifer properties across the area. Some very low test results could be the result of boreholes being drilled within buried glacial channels so that the thickness of Lower Cretaceous actually penetrated is less than it seems (see for example, Simon Hydrotechnica, 1992).

The reason for high transmissivity values in the Hillington area is not clear.

The degree of cementation is likely to affect groundwater flow mechanisms and hence aquifer properties. However, there is not sufficient information to attempt to investigate the relationship.

5.4.3.9 *Effects of structures*

There are no major structures in the area. In geomorphological terms, buried valleys present possible recharge routes through overlying Chalk and Gault Clay if they are sufficiently deep to see the Gault, but the importance of the mechanism would also depend on the type of glacial fill.

5.4.3.10 *Areal distribution of aquifer parameters*

There is no systematic spatial variation of transmissivity, which is not surprising given the lateral variation in lithology and thickness of the individual formations over short distances (Jackson, 1983). There does not appear to be a general reduction in transmissivity to the north or south as reported by McKelvey (1993). There were no results south of Marham, presumably due to the thinning and disappearance of the Leziate Beds as the Carstone Formation oversteps them.

5.5 THE LOWER CRETACEOUS/UPPER JURASSIC OF LINCOLNSHIRE

5.5.1 Introduction

The Lower Cretaceous/Upper Jurassic deposits are found again on the north side of The Wash in Lincolnshire. The term ‘Spilsby Sandstone’ has sometimes been used in this area to include all Lower Cretaceous sandstones, although it strictly refers only to the sediments of Ryazanian and Upper Jurassic age (see Table 5.1). Aquifers are frequently not correctly referenced and, as is the case for the Sandringham Sands of Norfolk, abstraction from the Roach and/or Carstone formations may be erroneously attributed to the Spilsby Sandstone. Papaioannou (1987) reports that, in particular, the northern extent of the aquifer is poorly understood, and there has been much confusion about whether certain boreholes have penetrated only to the Roach or Carstone formations but have been described as Spilsby Sandstone. Also, it is not uncommon for logs to describe the Carstone, Roach and Spilsby Sandstone as Greensand; in reality only the Carstone Formation is its lateral equivalent.

The Spilsby Sandstone was first used as a public source at the end of last century with a small development in Skegness, together with spring sources being used at Horncastle and Spilsby (Papaioannou, 1987). Due to its low TDS and hardness compared to Chalk groundwater, small developments have used the water for minor industry and steam generation.

The Elsham Sandstone, outcropping in the Elsham area, was originally thought to be an outlier of Spilsby Sandstone, but has now been dated as Lower Kimmeridgian based on faunal evidence (Gaunt et al., 1992). It is geologically and hydrogeologically distinct from the Spilsby Sandstone to the south (Papaioannou, 1987). As it is dated as Jurassic, it is covered in Section 6.3.3.9.

5.5.2 Geology and stratigraphy

5.5.2.1 *Extent of aquifer group, stratigraphy and lithology*

The Spilsby Sandstone (Strachan, 1886) is present in Lincolnshire from Grasby southwards, and in this direction eventually passes into the Sandringham Sands Formation of Norfolk (Casey and Gallois, 1973). Its outcrop lies along the foot of the Wold escarpment, from which it extends at depth towards the coast (Price, 1957), the maximum depth to the base being around 250 m near the mouth of the Humber. The sandstone thins to the north-west and south-east. The extent of the outcrop of the Lower Cretaceous deposits and aquifer test site locations is illustrated in Figure 5.34.

The Spilsby Sandstone rests unconformably on the Kimmeridge Clay and is sharply overlain by the Claxby Ironstone Formation. In north Norfolk the Spilsby Sandstone passes laterally into the Mintlyn, Roxham and Runcton beds of the Sandringham Sands Formation. The Spilsby Sandstone represents the north-western part of a marginal marine quartzose sand facies deposited between the Market Weighton High and the East Anglian Massif.

Two members are recognised within the Spilsby Sandstone, the Lower Spilsby Sandstone and the Upper Spilsby Sandstone (Gaunt et al., 1992) with a combined thickness of about 30 m. They are almost identical lithologically and each has a prominent basal nodule bed containing phosphatised pebbles and derived fossils. The formation spans the Jurassic-Cretaceous boundary.

The Lower Spilsby Sandstone is broadly equivalent to the Runcton Beds of north Norfolk. The Lower Spilsby Sandstone is unconsolidated, but encloses masses of hard sandstone with a calcite cement. It gradually thickens southwards to between 8 and 10 m at Caistor, but may reach 18 m where it apparently fills incised channels. The basal Spilsby Sandstone Nodule Bed, although less than 0.15 m thick, contains numerous phosphatised pebbles, 6 to 12 mm in diameter. The remainder of the Lower Spilsby Sandstone is a relatively homogeneous quartzose sandstone that varies in colour and in its content of phosphatic pebbles,

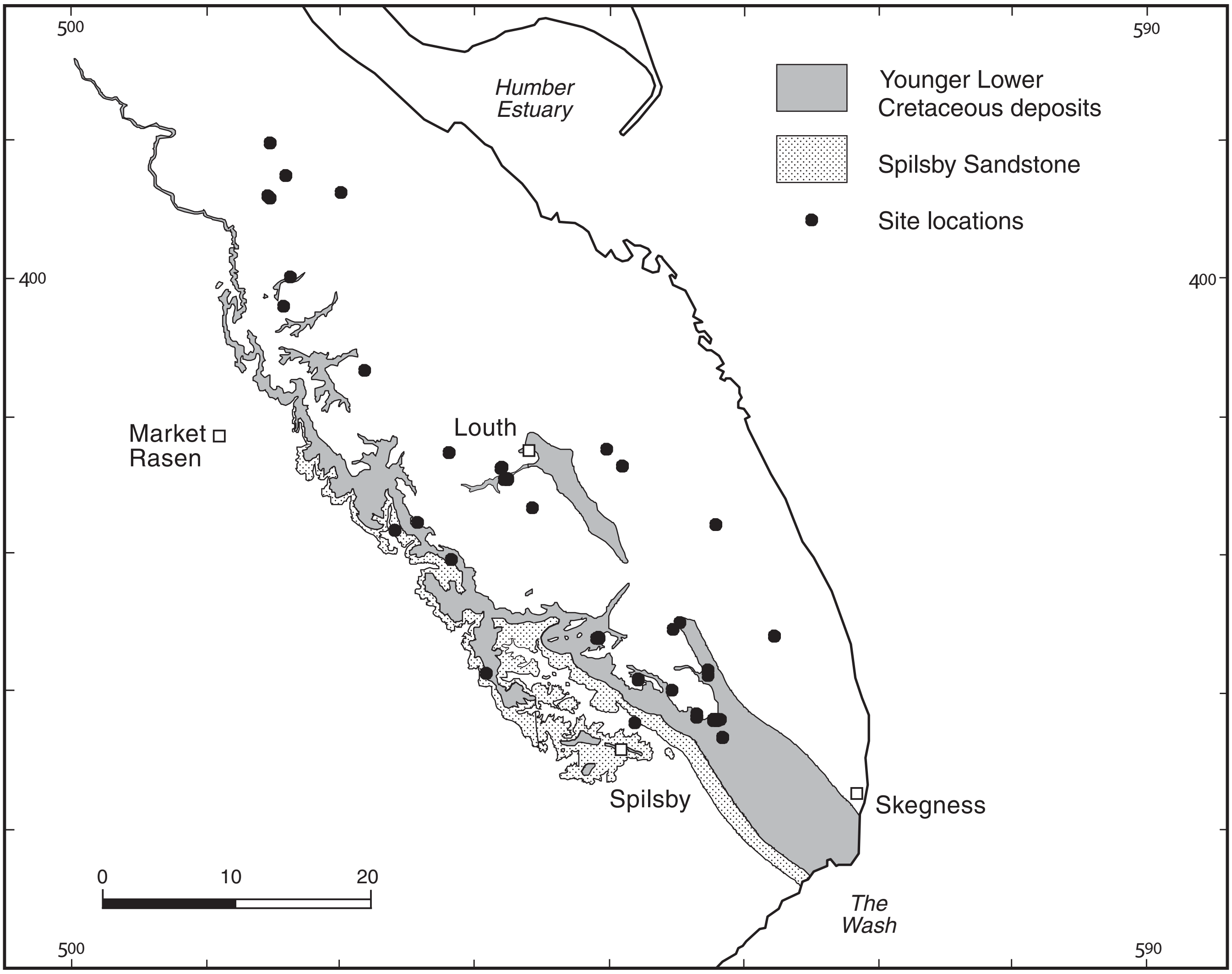


Figure 5.34 Outcrop of Lower Cretaceous/uppermost Jurassic rocks in Lincolnshire.

silt and clay. The sandstone varies from calcareous quartzose grit to friable, medium-grained, quartz sand with silt and clay admixtures. The grains are mainly subangular and polished.

The Upper Spilsby Sandstone has a maximum thickness of at least 11 m and rests on the eroded top of the Lower Spilsby Sandstone. It extends from Hundon Manor [TA 1179 0252] south through Lincolnshire and is broadly equivalent to the Mintlyn Beds of north Norfolk. The basal layer of the Upper Spilsby Sandstone, the Mid Spilsby Nodule Bed, closely resembles the Lower Spilsby Nodule Bed, but its phosphate content is lower. The remainder of the Upper Spilsby Sandstone consists of quartzose sandstone that is partly calcitic, and partly decalcified and friable. The degree of cementation is variable.

There is a sharp transition from the Spilsby Sandstone to the overlying Claxby Ironstone Formation. (Kent, 1980), although locally, the Hundleby Clay may intervene. The Claxby Ironstone Formation is broadly equivalent to the Leziate Beds of Norfolk. The Hundleby Clay is considered to be equivalent to the upper part of the Mintlyn Beds in north Norfolk. The Claxby Ironstone Formation is represented by an oolitic ironstone up to 5 m thick. This becomes shaley south-eastwards, as it changes to the Hundleby Clay facies, although ironstone intercalations are still present as far south as Spilsby.

The Tealby Beds, approximately 20 m thick, succeed the Claxby Ironstone (or Hundleby Clay in the south), and are sub-divided into the Lower Tealby Clay, the Tealby Limestone, and the Upper Tealby Clay (Kent, 1980). The Tealby Limestone is a productive and well-marked horizon, between 1 and 4 m thick, comprising alternating argillaceous or sandy limestones with clay partings. This passes into a clay facies to the south-east, near Fordington (Price, 1957).

The maximum thickness of the overlying Roach Formation (also known as the Fulletby Beds) is probably around 23 m in south Lincolnshire. In northern Lincolnshire it is up to 11.5 m thick near Walesby [TF 13 92], but it thins northwards and is absent at outcrop north of Nettleton Bottom [TF 1257 9856]. The base of the Roach Formation in Lincolnshire is taken at a minor erosion surface that separates its predominantly oolitic and pebbly clays from the smoother-textured, more fossiliferous clays of the Tealby Beds. The formation in north Lincolnshire commences with a ferruginous limestone some 3 m thick, overlain by a complex sequence of highly ferruginous limestones, mudstones, and sandstones.

Increasing amounts of sandy material and glauconite mark the overlying Carstone Formation. This coarsens upwards from fine sand to coarse grit. There are indications of a stratigraphic break in the middle part, and only the upper coarse, gritty part is now regarded as Carstone Formation (Kent, 1980). The formation is approximately 10 m thick at Langton, but thins north-west along the outcrop (Price, 1957). At its top, the coarse grits are intercalated with the relatively impermeable yellow and red marls of the Red Chalk. These transgress across the underlying Lower Cretaceous rocks northwards, and come to rest on Jurassic rocks north of Caistor (Kent, 1980).

From Louth, to Skegness in the south-east, is a buried cliff line, marking the location of an old coastline. The cliff has been infilled with glacial deposits. At the base of the cliff line, the erosion has cut through the Chalk and into the underlying sands and clays (Groundwater Development Consultants, 1989), as shown in Figure 5.35. The existence of the buried cliff line affects the hydrogeological regime in this area, as discussed in Section 5.5.3.

5.5.2.2 *Depositional history*

The depositional history is similar to that south of The Wash, and is included within Section 5.4.2.2.

5.5.2.3 *Structures*

The Lower Cretaceous/Upper Jurassic rocks of east Lincolnshire formed a fairly rigid block that was tilted to the north-east by the Alpine orogeny (Groundwater Development Consultants Ltd, 1989). This has resulted in a gentle and fairly uniform dip to the north-east across the area.

The only major fold affecting the Cretaceous rocks in Lincolnshire is the Caistor monocline, running from the end of the Spilsby outcrop near Grasby, north-east towards Grimsby. The monocline has a downthrow of between 40 and 80 m on its northern side (University of Birmingham, 1979).

There do not appear to be any major faults affecting the Spilsby Sandstone, although minor faults and joints are thought to be common (George, 1979).

5.5.3 Hydrogeology

5.5.3.1 *Introduction*

The Lower Cretaceous/Upper Jurassic deposits comprise alternating aquiferous horizons, mainly sandstones (the Spilsby Sandstone, Carstone Formation, Roach Formation, and Tealby Limestone), with impermeable confining layers such as the Tealby Clay and Sutterby Marl. The Spilsby Sandstone is the most important and is generally confined above and below by the Tealby Clay and Kimmeridge Clay respectively (Mason, 1992). Its high porosity results in a useful aquifer that produces copious springs; some of these have contributed to the development of landslips and mudflows along the Lincolnshire Wolds scarp. However, construction of boreholes and development of the aquifer have proved difficult due to the lack of cementation (Papaioannou, 1987). The widespread presence of loose sand that may enter into the borehole has led to the common practice of

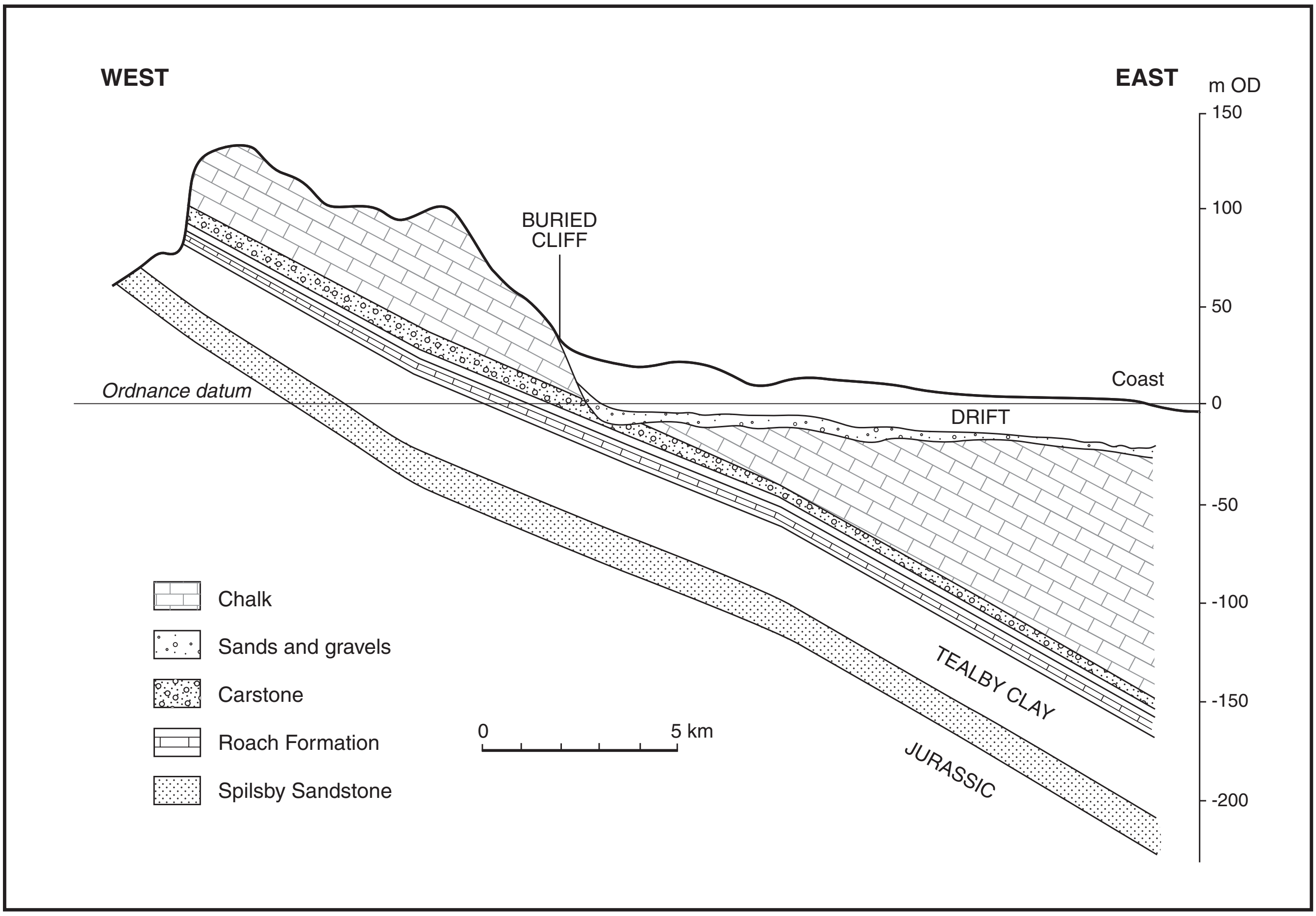


Figure 5.35 Section across the Lincolnshire Wolds showing stratigraphic relationships between the various aquifer systems and significance of the buried cliff line (from Groundwater Development Consultants, 1989).

developing boreholes by pumping at rates well in excess of the design peak abstraction rate. The boreholes then yield relatively sand free water when pumping at typical abstraction rates (Papaioannou, 1987). This has tended to work relatively well, although fine sand is sometimes still encountered when pumping rates are reduced.

Above the Spilsby Sandstone, the Tealby Formation, Roach Formation, and Carstone Formation represent relatively minor aquifers. The Tealby Limestone itself is a thin and impersistent aquifer (Mason, 1992). It has been reported as having a low yield, and containing water of poor quality, indicating long residence times and poor aquifer characteristics (George, 1979). The Roach Formation is a more important minor aquifer from which small private supplies are obtained. The Carstone Formation was formerly exploited for public water supply at a relatively small development at Binbrook (Groundwater Development Consultants Ltd, 1989). There are probably many private boreholes abstracting small supplies from the formation.

As data were only available for the Spilsby Sandstone (with one exception), the following sections refer to this formation, unless specific reference is made to other Lower Cretaceous aquifers. However, as previously mentioned, it should be noted that the 'Spilsby Sandstone' has been used in the past as a generic term for all the Lower Cretaceous sandstones.

5.5.3.2 *Previous studies*

The first investigation of the hydrogeology of the Spilsby Sandstone appears to have been by Price (1957). In the mid 1980s, the formation was recognised to be an important groundwater resource, although the aquifer's hydrogeology was insufficiently understood to allow assessment of its full resources potential and enable its optimum development. As a result, the Spilsby Sandstone investigation was carried out, involving detailed investigation of the aquifer. This included some modelling and assessment of resource potential (Papaioannou, 1987; Groundwater Development Consultants Ltd, 1989).

5.5.3.3 *Groundwater flow and recharge*

Over much of the area, groundwater flow follows, approximately, the dip of the Spilsby Sandstone (Price, 1957). In the north-west, near the Caistor Monocline, the contours of the potentiometric surface become oblique to the dip and, as the sandstone thins, the gradient becomes steeper (Price, 1957). In the south, the potentiometric surface contours swing round to a south-westerly direction, and again the hydraulic gradient steepens. Price suggested that the steepening in both areas could be a function of a decrease in transmissivity, possibly associated with the thinning of the Spilsby Sandstone. Groundwater Development Consultants Ltd (1989) suggest that, based on potentiometric and water quality information, very little groundwater flow occurs in the south of the area.

The potentiometric surface for the Spilsby Sandstone has been modified appreciably in the last 50 years or so by the development of public water supply sources (Price, 1957; Groundwater Development Consultants Ltd, 1989). There are now zones of depression around Raithby [TF 31 84] and Hubbards Hill near Louth, and around Welton le Marsh [TF 47 68] and Candlesby [TF 45 67] in the south of the area.

Recharge occurs along the narrow outcrop or through permeable drift (Price, 1957). Direct recharge to the Spilsby Sandstone aquifer has been estimated to average approximately 240 mm/a, equivalent to a daily resource of around 51×103 m^3/d (Papaioannou, 1987). However, the majority of recharge feeds springs on the escarpment and is lost from the aquifer (Groundwater Development Consultants, 1989). Additional recharge may be provided by springs issuing from the sandstones above the Spilsby Sandstone and draining down the escarpment. Runoff from clay outcrops also provides recharge to aquifers lower in the sequence.

Recharge to the confined Spilsby Sandstone is thought to occur through leakage from confining beds, and the degree of hydraulic connection is considered an important factor in assessing resource potential for the aquifer (Groundwater Development Consultants Ltd, 1989). The relationships between the Chalk potentiometric surface and those of the Lower Cretaceous sandstone aquifers are not simple. To the west of the area of the buried cliff line the Chalk potentiometric surface elevation is above that of the Cretaceous sandstones. It has been suggested that recharge to the confined Spilsby Sandstone in this area occurs indirectly through downward leakage from the Chalk (see Figure 5.36) (Groundwater Development Consultants, 1989). The intervening presence of the Tealby and Skegness Clays and the Sutterby Marl south of the Caistor Monocline would question this interpretation but Groundwater Development Consultants (1989) imply that the intervening minor clays, sandstones, limestones and ironstones have little significance with respect to leakage between the two aquifers. It has been suggested that, given the area over which the aquifers extend, even with low overall vertical hydraulic conductivity, significant volumes of water do transfer between the two aquifers (Peter McConvey, personal communication). Modelling by Groundwater Development Consultants Ltd (1989) suggested that between 10 and 25% of the direct recharge to the Chalk could be lost through leakage to the underlying sandstones. Mason (1992) also suggested that around 22% of Chalk water was lost as leakage specifically to the Spilsby Sandstone.

Groundwater flow is believed to occur from west of the buried cliff line, to the confined Spilsby Sandstone aquifer to the east, providing recharge to the eastern area. However, in the region of the cliff line the potentiometric surface of the Cretaceous sandstones rises above that of the Chalk, and consequently to the east there may be some upward leakage of water back into the Chalk. This interaction between the Chalk and underlying sandstones means that they have to be considered as interdependent hydrogeological units, which has important repercussions for groundwater management. Development of a combined Lincolnshire Chalk/Spilsby Sandstone resource model by the Environment Agency began in late 1999. A much clearer understanding of the hydraulic relationship between these two aquifers should be achieved upon completion of this work (Peter McConvey, personal communication).

Groundwater hydrographs from adjacent Chalk and Carstone boreholes at Belleau [TF 401 779] and Burwell [TF 351 795] indicate that continuity is well developed between the two aquifers in the area (Allen et al., 1997). At Burwell in the west, downward leakage is thought to occur from the Chalk to the Carstone Formation; further east this reverses, and flow is from the Carstone to the Chalk, and then to baseflow. Further east again, the Chalk thickens and its continuity with the Lower Cretaceous aquifers is lost. Despite the apparent continuity between the Chalk and lower aquifers, permeability studies, modelling work, and hydrochemical analyses suggest the amount of groundwater flow across the buried cliff line is small (University of Birmingham, 1978).

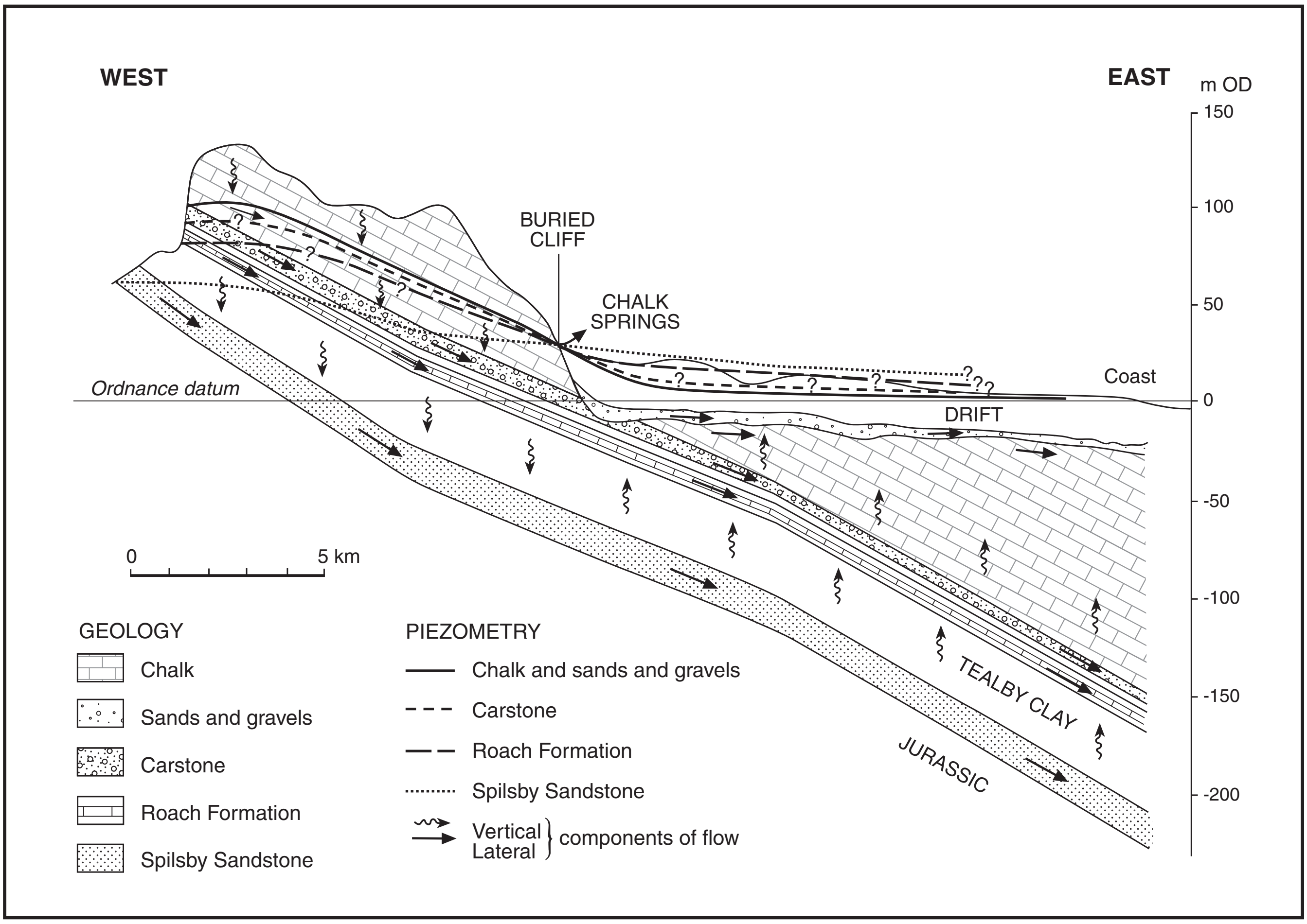


Figure 5.36 Schematic section showing theoretical groundwater flow systems across the Lincolnshire Wolds (from Groundwater Development Consultants, 1989).

5.5.3.4 *Nature and extent of confinement*

As in Norfolk, the alternating lithologies of the Lower Cretaceous/Upper Jurassic formations create a multi-aquifer system, further complicated by lateral facies changes. The more argillaceous layers (including the Hundleby Clay, Tealby Clays, Sutterby Marl) act as confining beds although, as previously discussed, the degree of leakage between different formations, and between the Lower Cretaceous and the Chalk, is not always clear (see Section 5.5.3.3). Although the Chalk is nowhere in direct contact with the Spilsby Sandstone, there may be hydraulic connection via the Carstone Formation and/or superficial deposits (Papaioannou, 1987).

Thick (200 to 350 m) Upper Jurassic clays, immediately beneath the Spilsby Sandstone, form the base of the aquifer system. The Spilsby Sandstone itself is usually confined by the clays of the Tealby Beds (Groundwater Development Consultants Ltd, 1989; Mason, 1992). North of the Caistor Monocline, the Tealby Beds are absent and it may be in hydraulic continuity with the Carstone Formation (George, 1979).

The Roach Formation is separated from the Spilsby Sandstone by the Tealby Clay, and from the Carstone Formation by the Sutterby Marl (Mason, 1992).

The Red Chalk separates the Chalk and Carstone Formation, and is often considered to be an aquitard. However, locally, where it has been fractured or has joints, it may be considered as an aquifer, allowing hydraulic continuity between the formations (Mason, 1992). Papaioannou (1987) suggests this is quite likely in the vicinity of the Caistor Monocline due to the large displacement and development of joints and faults. At Burwell [TF 351 795], some distance south of the monocline, water level hydrographs for the Chalk and Carstone Formation indicate that continuity may exist away from the monocline (Mason, 1992).

Where they are in contact with the Spilsby Sandstone, glacial sands and gravels may contribute to the available resources of the aquifer (Groundwater Development Consultants Ltd, 1989; Mason, 1992). South-east of the outcrop area, the contact between the Spilsby Sandstone and drift deposits is below present sea level, and the drift deposits are nearly saturated (Mason, 1992). The potentiometric relationship between the superficial groundwaters and those in the Spilsby Sandstone could be important with respect to groundwater movement through this area.

5.5.3.5 *Aquifer properties*

Groundwater movement in the Spilsby Sandstone is primarily intergranular, although there may be movement along joints and fractures in the more cemented parts of the aquifer (Papaioannou, 1987), that is generally in the south and east of the area (Groundwater Development Consultants Ltd 1989). Permeability may be reduced in some areas due to the silt content, for example south of Louth (Papaioannou, 1987). Groundwater Development Consultants Ltd (1989) reported that grain size varies from one locality to another, although it appeared that the formation is generally finer in the south than elsewhere.

It has been reported that aquifer permeability is increased in the vicinity of pumping boreholes due to the removal of sand. However, although improving the productivity of the abstraction, this has implications for the long-term structural integrity of the wells concerned.

Groundwater Development Consultants Ltd (1989) reported that the highest transmissivity (and greatest thickness) occurs around Raithby and Hubbards Hill; coincidentally the Spilsby Sandstone appears to be coarser and thicker, and has fewer hard layers, in this area. Transmissivity values were reported to be low to the south. The reported values of transmissivity for the Spilsby Sandstone were mainly in the range 130 to 170 m^2/d, with 800 m^2/d recorded at Hubbards Hill. These values are slightly higher than previously published values of between 30 and 160 m^2/d (Gale et al., 1983). Papaioannou (1987) reported values of transmissivity between 50 and 400 m^2/d, with storage coefficients ranging between 10^{-4} and 10^{-3}. Higher values from the Welton le Marsh area could reflect higher local storage due to near-well development of the aquifer during pumping (Groundwater Development Consultants Ltd, 1989). There were insufficient reliable data available to discern any definite regional trends.

5.5.3.6 *Pumping test results*

The data collected for this project were mostly for the confined aquifer (Table 5.9, Figure 5.37). Values range from 6 to 1000 m^2/d, with an interquartile range of 90 to 250 m^2/d, and a geometric mean of 141 m^2/d. The data are distributed approximately log-normally. The highest transmissivity values (greater than 1000 m^2/d) tended to be not in the centre but north of the Caistor Monocline, around the Keelby area; high values were not associated with outcrop of the Spilsby Sandstone. No values were available for the southern end of the sandstone subcrop where it is covered by drift, suggesting it is little used in this area. The calculated storage coefficients range from 0.00006 to 0.0063, with a geometric mean of 0.0004 (Figure 5.38). This range of values reflects the location of tests in the confined part of the aquifer.

Specific capacity values range from 2.4 to 237 m^3/d/m, with an interquartile range of 28 to 179 m^3/d/m, and a geometric mean of 69 m^3/d/m. The distribution is heavily skewed to the left, that is, there are a large number of higher values (Figure 5.39). The reasons for this are not clear.

There is a positive correlation between specific capacity and transmissivity (see Figure 5.40) although the coefficient

Table 5.9 Summary of pumping test results for the Spilsby Sandstone.

Spilsby Sandstone records		
Total number of records	77	—
Number of transmissivity values	67	—
Minimum/maximum transmissivity value (m^2/d)	6.0	1000
Arithmetic/geometric mean of transmissivity (m^2/d)	206	141
Median/interquartile range of transmissivity (m^2/d)	176	160
25/75 percentile of transmissivity (m^2/d)	90.4	250
Number of storage coefficient values	24	—
Minimum/maximum storage coefficient value	6×10^{-5}	6.3×10^{-3}
Arithmetic/geometric mean of storage coefficient	8×10^{-4}	4×10^{-4}
Number of specific capacity values	29	—
Minimum/maximum specific capacity value (m^3/d/m)	2.37	238
Arithmetic/geometric mean of specific capacity (m^3/d/m)	110	69.0
Median/interquartile range specific capacity (m^3/d/m)	136	152
25/75 percentile of transmissivity (m^3/d/m)	27.6	179

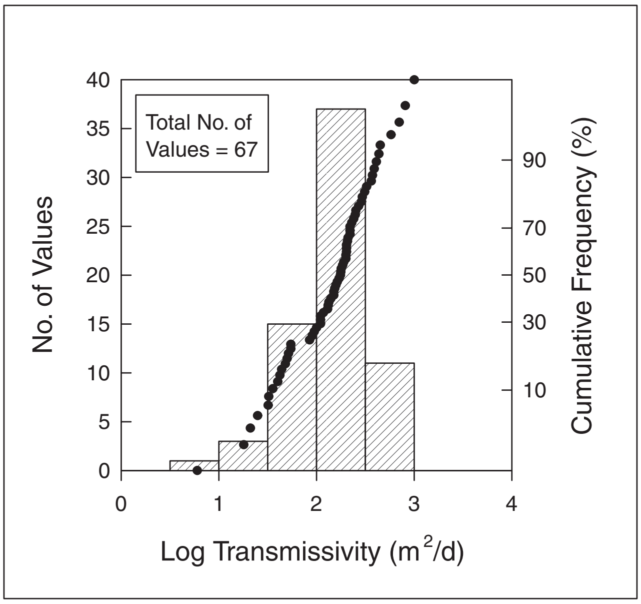


Figure 5.37 Distribution of transmissivity values from pumping tests in the Spilsby Sandstone.

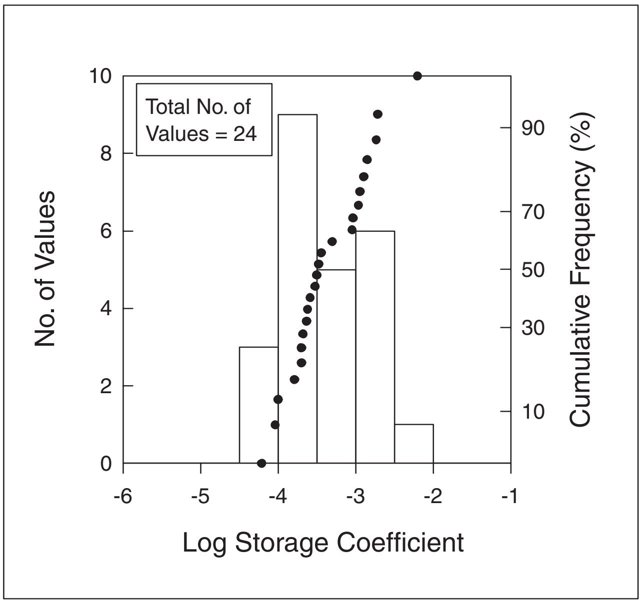


Figure 5.38 Distribution of storage coefficient values from pumping tests in the Spilsby Sandstone.

of determination (r^2) is only 0.55. For areas where few pumping test results are available, specific capacities could provide an indication of the physical properties of the aquifer.

5.5.3.7 *Yield data*

Papaioannou (1987) reported average yields of around 1700 m^3/d, although up to 4320 m^3/d were known. Monkhouse and Richards (1982) suggested typical yields were around 2600 m^3/d, up to a maximum of around 10 000 m^3/d. Data obtained during this project gave a range between 30 and 6000 m^3/d, the higher values tending to be in the Louth area, and some to the south. However, there was generally no systematic pattern to the yield distribution.

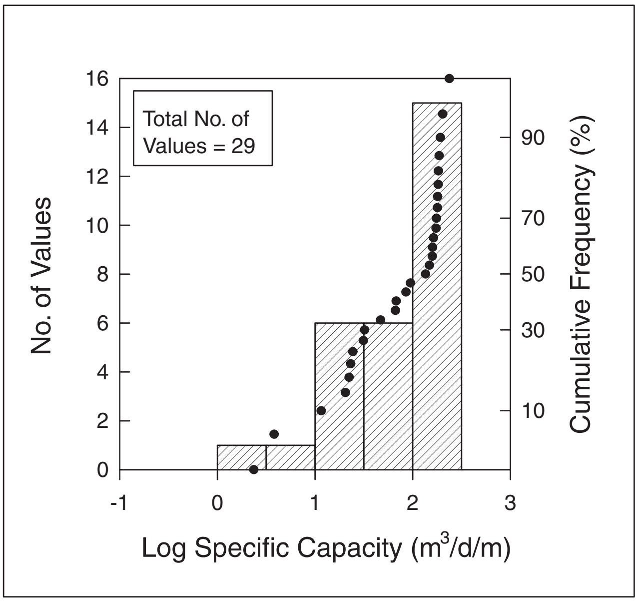


Figure 5.39 Distribution of specific capacity values from pumping tests in the Spilsby Sandstone.

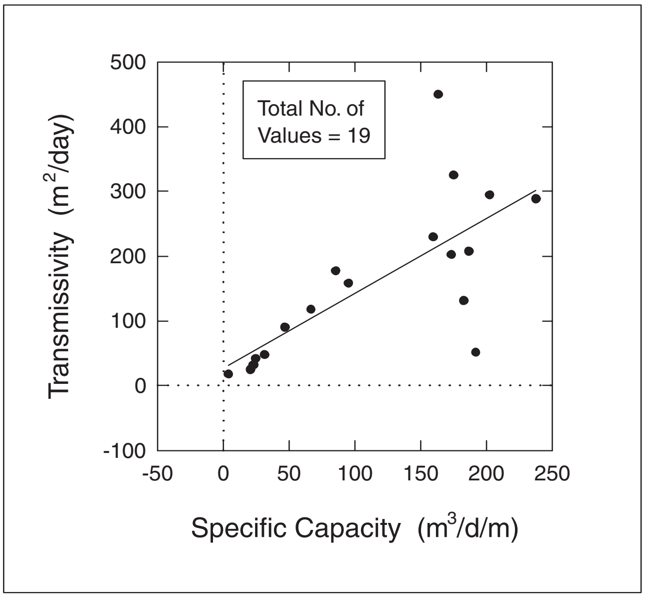


Figure 5.40 Correlation between transmissivity and specific capacity for the Spilsby Sandstone.

5.5.3.8 *Controls on permeability and transmissivity*

The degree of cementation is likely to affect aquifer properties. Papaioannou (1987) suggested that more cemented areas exhibited markedly lower transmissivities than uncemented areas, although there was insufficient evidence from this study to confirm this.

Locally, transmissivity may also be enhanced due to greater aquifer thickness, coarser grain size, or auto-development and sand removal in the vicinity of a pumping borehole.

5.5.3.9 *Effects of structures*

In the area of the Caistor Monocline, small scale jointing and faulting may provide a hydraulic connection permitting groundwater flow between the Chalk, Carstone Formation and Spilsby Sandstone (Papaioannou, 1987).

The role of the buried cliff line regarding groundwater movement is not clear. Where the Chalk and lower Cretaceous aquifers are in hydraulic continuity, there is potential for the latter to transport water across the cliff line, the water then leaking back into the Chalk where the relative potentiometric levels reverse to the east (see Section 5.5.3.3). However, as described in Section 5.5.3.3, previous work has suggested that the amount of groundwater flow across the cliff line by this mechanism is very small.

5.5.3.10 *Areal distribution of aquifer parameters*

There appeared to be no systematic variation of aquifer properties using the data collected as part of this project. Although transmissivity values have been reported to be low in the south of the area (Groundwater Development Consultants Ltd, 1989), no evidence could be found for this from the data, other than the absence of data in the far south. Locally, high transmissivity values may be attributed to a number of factors (see Section 5.5.3.8). As previously mentioned, the highest values of transmissivity (greater than 1000 m^2/d) tended to be north of the Caistor Monocline, around the Keelby area; these boreholes are very close to the northern limit of the sandstone, which thins out and is overstepped by the Carstone Formation in the area. The high values therefore appear anomalous, and could be from Carstone sources, possibly in hydraulic contact with the Chalk and erroneously ascribed to the Spilsby Sandstone.

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6 Jurassic minor aquifers

6.1 INTRODUCTION

Rocks of Jurassic age crop out in a broad band trending south-west to north-east from Dorset to the Yorkshire and Cleveland coasts (Figure 6.1). They are present at depth beneath Cretaceous rocks over all of eastern England except south-eastern East Anglia, and the London and north Kent areas. West of the main outcrop, Lower Jurassic outliers occur in Cumbria, in Glamorgan, on the Shropshire-Cheshire borders and on the margin of Cardigan Bay. This chapter describes the aquifer properties of the less important Jurassic aquifers, and complements Chapter 6 in Allen et al. (1997). The latter describes the major Jurassic aquifers: these principally comprise limestones of Aalenian, Bajocian, and Bathonian age, with subsidiary friable sandstones.

This chapter divides the Jurassic strata into two geographical areas: north and south of the Market Weighton Axis (see below). For each area, the geology and stratigraphy of the Jurassic strata are described, followed by their hydrogeology and aquifer properties. In some cases, although the geology and stratigraphy are summarised in this chapter, there is no information regarding their hydrogeology or aquifer properties.

From a hydrogeological standpoint it is unfortunate that, although the Jurassic has been the subject of geological research since the 18th century, and the geology and stratigraphy are well understood, intricately sub-classified, and exhaustively mapped, there is no such detailed knowledge documented for its hydrogeology. As a result, the rocks tend to be lithologically minutely sub-divided, though hydrogeologically oversimplified. This chapter reflects the current unsatisfactory position.

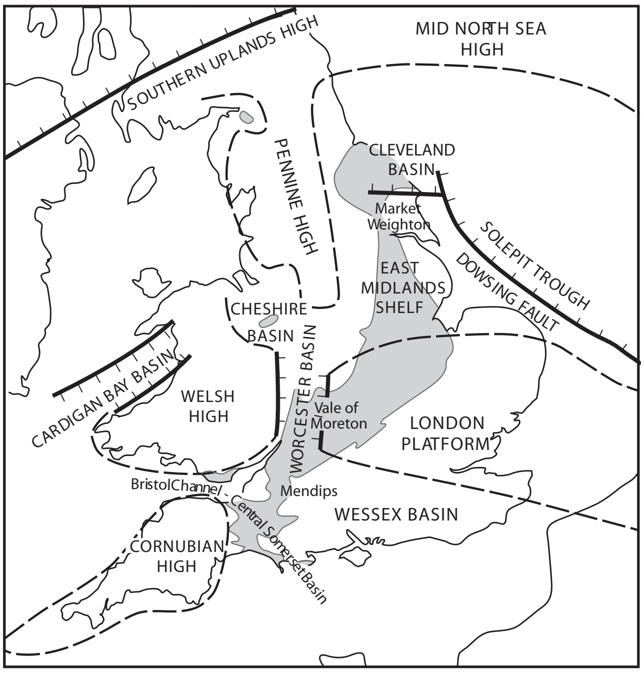

Figure 6.1 Outcrop area and principal structural features of the Jurassic (after Hallam, 1992).

6.1.1 General geology

The Jurassic sediments are up to 1500 m thick and generally dip gently eastwards. They were mainly laid down under tropical climatic conditions in water of less than 100 m depth. There are thought to have been three different depositional environments (Hallam, 1992):

- deep shelf (clays)
- shallow shelf (carbonates and sandstones)
- marginal marine to non-marine including
  - — lagoons and supratidal flats (fine-grained calcareous and argillaceous deposits)
  - — coastal swamps and marshes (silts and clays with rootlets)
  - — river deltas and flood plains (sandstones, siltstones and carbonaceous shales).

Where the sequence contains a high proportion of limestones this indicates a low influx of clastic material from neighbouring land areas. The general absence of debris-flow deposits, turbidites and slumping implies that depositional slopes were extremely low (Hallam, 1992).

Sedimentation was also controlled by a series of platforms and highs, separating basins and shelves. Relatively thin sequences were deposited on the highs, most or all of which have subsequently been removed by erosion; thicker sequences occur in the basins and shelves. The Mendips, Vale of Moreton and Market Weighton axes therefore separate the four main depositional areas: Wessex Basin (including Bristol Channel — Central Somerset), Worcester Basin and Cotswolds, East Midlands Shelf, and Cleveland Basin. The sequence is different in each, although the first two are very similar (Table 6.1). However, these highs were not effective throughout the Jurassic, for example, the Vale of Moreton Axis did not affect deposition in Upper Jurassic times, and some sedimentation occurred across the axes. This is particularly true of the more minor aquifers and the argillaceous deposits which tended to be deposited on the margins of the basins. This report divides the country into two areas, that is, north and south of the Market Weighton Axis: the division is unequal, but logical, as not only the sequences but the formation names are very different in the two areas. Within both areas, the deposits are dealt with in ascending stratigraphic order, and the regional variations within the area south of Market Weighton are generally described from the north to the south of the country.

Jurassic sedimentation was affected, throughout England, by a series of transgressions and regressions. The first transgression was in early Jurassic times with a predominantly clay sequence overstepping rocks varying in age from latest Triassic to Palaeozoic. A regression followed in the early Mid Jurassic which commenced with the replacement of marine sediments by non-marine deltaic sediments in northern and part of central England. This was followed

Table 6.1 Typical successions of Jurassic rocks in the four principal depositional areas (adapted from Hallam, 1992).

STAGES	GROUP	WESSEX BASIN (Dorset)	WORCESTER BASIN AND COTSWOLDS (Avon to Oxon)	EAST MIDLANDS SHELF (Northants to Lincs)	CLEVELAND BASIN
PORTLANDIAN	Portland Group	Lulworth Beds Portland Limestone Portland Sand	Purbeck' Beds Portland Beds	Lower Spilsby Sandstone	
KIMMERIDGIAN		Kimmeridge Clay	Kimmeridge Clay	Kimmeridge Clay	Kimmeridge Clay
OXFORDIAN	Corallian Group	Sandsfoot Grit Sandsfoot Clay Clavellata Beds Osmington Oolite Nothe Clay Nothe Grit Upper Oxford Clay*	Coral Rag, Wheatley Limestones, etc. Lower Calcareous Grit Upper Oxford Clay*	Ampthill Clay West Walton Formation Upper Oxford Clay*	Ampthill Clay Upper Calcareous Grit Coralline Oolite Lower Calcareous Grit Oxford Clay
CALLOVIAN		Middle Oxford Clay* Lower Oxford Clay* Kellaways Formation Upper Cornbrash	Middle Oxford Clay* Lower Oxford Clay* Kellaways Formation Upper Cornbrash	Middle Oxford Clay* Lower Oxford Clay* Kellaways Formation Upper Cornbrash	Hackness Rock Langdale Beds Kellaways Rock Cornbrash
BATHONIAN	Great Oolite Group	Lower Cornbrash Forest Marble Upper Fuller's Earth Clay Fuller's Earth Rock Lower Fuller's Earth Clay	Lower Cornbrash Forest Marble Great Oolite Upper FE Clay Fuller's Earth Rock Lower FE Clay White Limestone Hampen Formation Taynton Limestone Fuller's Earth/Sharp's Hill Formation Chipping Norton Fm	Lower Cornbrash Blisworth Clay Blisworth Limestone Rutland Formation	Scalby Formation
BAJOCIAN Formation	Inferior Oolite Group	Upper Inferior Oolite Middle Inferior Oolite	Upper Inferior Oolite Middle Inferior Oolite	Lincolnshire Limestone	Scarborough Cloughton Formation Eller Beck Formation
AALENIAN		Lower Inferior Oolite	Lower Inferior Oolite	Grantham Formation Northampton Sand Formation	Saltwick Formation Dogger Formation
TOARCIAN	Lias Group	Bridport Sand Downcliff Clay	Bridport Sands and Whitby Mudstone	Upper Lias Clay	Blea Wyke Sand; Peak Shales, etc.; Alum Shale; Jet Rock etc.; Grey Shales
PLIENSBACHIAN		Junction Bed Thorncombe Sand Eype Clay, etc. Green Ammonite Beds Belemnite Marls	Marlstone Dyrham Formation Charmouth Mudstone	Marlstone Dyrham Formation Charmouth Mudstone, incl. Pecten Ironstone	Cleveland Ironstone Staithes Formation Redcar Mudstone Formation (including Ironstone Shales etc.,
SINEMURIAN		Black Ven Marls Shales with Beef Blue Lias	Blue Lias	Frodingham Ironstone Scunthorpe Mudstone	Siliceous Shales, Calcareous Shales, Shales at Redcar)
HETTANGIAN					

* Upper, Middle and Lower Oxford Clay are now the Weymouth, Stewartby and Peterborough members respectively.

by large-scale limestone deposition during Aalenian to Bathonian times, except in the Cleveland Basin. A second transgression starting in late Bathonian times was followed by a long period of clay deposition. A final major regression occurred at the end of the Jurassic, with the sequence shallowing from the Kimmeridge Clay through the Portland Beds to the marginal marine or non-marine Lulworth Beds of Dorset. Therefore the majority of the sequence comprises shales and clays, with limestones and sandstones forming a relatively small part of the total thickness, and their position and importance varying from area to area. The relative thicknesses of the various deposits are shown in Figure 6.2.

6.1.2 General hydrogeology

The permeable parts of the Jurassic sequence are the limestones and subordinate sandstones, including ferruginous sandstones ('ironstones'). These aquifers are relatively thin and rarely extend over large areas. Therefore within a single depositional area, aquifer units may be laterally discontinuous over distances of kilometres or less. In addition as the

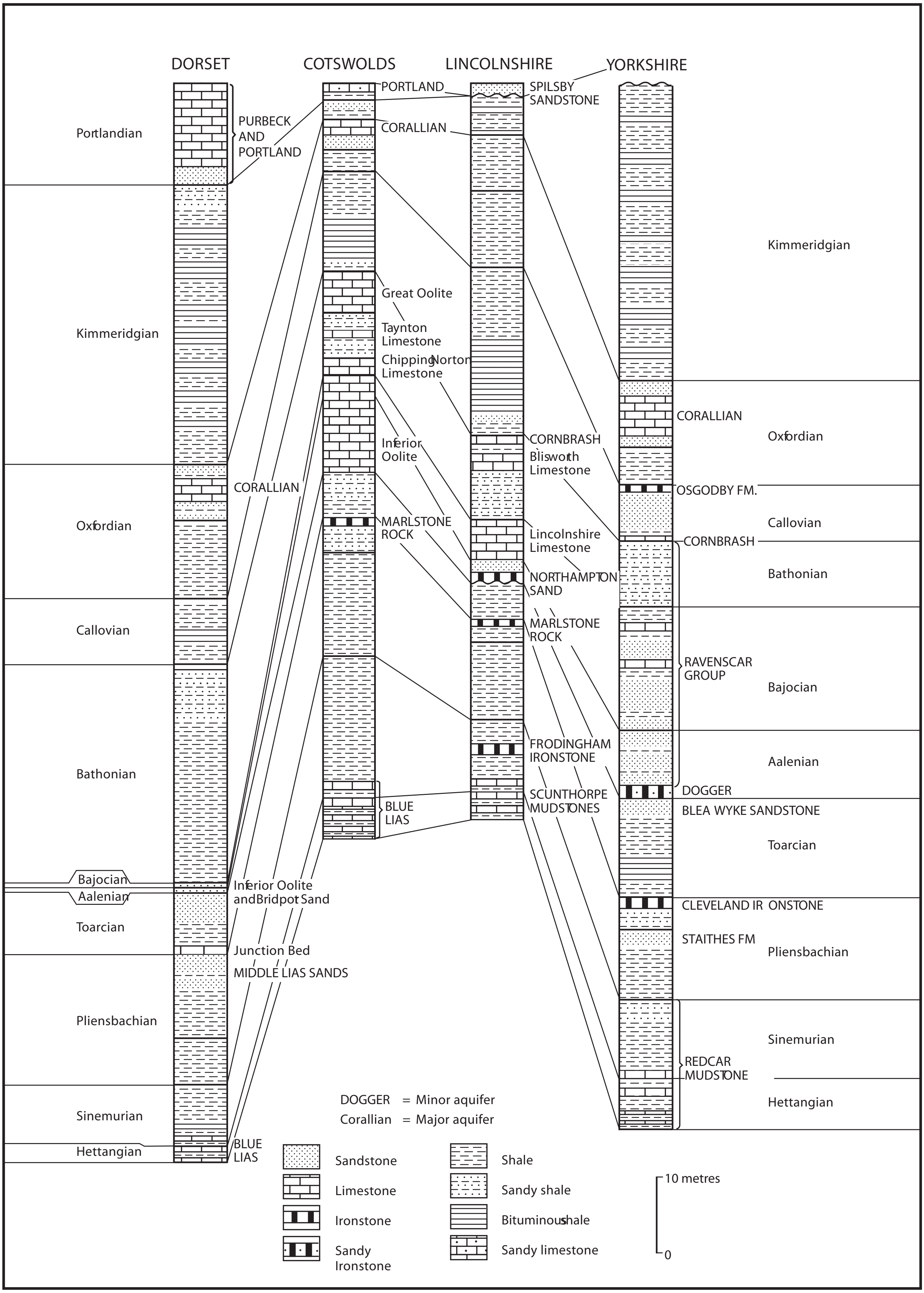

Figure 6.2 Principal facies and thickness variations in the Jurassic, illustrated by lithostratigraphic columns from the four main depositional basins (after Hallam, 1992).

aquifer units are relatively thin, faults with quite limited displacements may split an aquifer into separate, hydraulically isolated compartments. Similarly, faults may juxtapose different aquifers placing them in hydraulic continuity.

The overlying and underlying strata are generally clays, therefore the limestones form distinctive scarps, often with deeply incised valleys, that rise well above the surrounding clay vales. In the unconfined portion of the aquifer, the unsaturated zone is often thick, and unless wells are fully penetrating they are frequently dry for part of the year. Springs are common at the boundaries with underlying less permeable formations and at faulted junctions.

Intergranular permeabilities are generally low in the limestones and water movement takes place through fractures. In the limestones, these have often been enlarged by solution. These openings are irregularly distributed in a vertical and horizontal sense, but may extend for significant distances and where interconnected, may result in high yields. Therefore yields are variable depending on whether or not a borehole intersects an interconnected system of water-filled openings. However, unlike the Palaeozoic limestones, few completely dry wells have been drilled. This may imply a greater density of linked microfissures or a low, but not insignificant, primary porosity. Locally, karstic features have been noted in the main limestone aquifers. Horizontal permeabilities are generally higher than vertical ones due to the presence of clay-rich layers within the limestones. The sandstones, friable sands, and ironstones have not been investigated hydrogeologically in any great detail, but fracture development in these arenaceous beds is likely to be less pronounced than in the limestones, and primary porosity may play a greater role in water storage and transport. Controls on permeability are more closely linked to the degree of induration and grain size distribution. In extreme cases, cementation results in the formation of low permeability, concretionary horizons, as in the ironstones, but varying degrees of cementation with siderite or chamosite are widely found.

Although the Jurassic limestone aquifers are characterised by high secondary permeabilities, as the minor aquifers are generally thin, transmissivities are relatively low. They also have low storage coefficients. Water resources are limited, both yields and water levels often falling significantly after only a few hours pumping. Furthermore, where formations are highly fissured pumping can affect sources some distance away. At outcrop the aquifers respond rapidly to recharge and are characterised by large seasonal variations in water levels (20 m is not uncommon near the interfluves) and effluent rivers. The fast response times, and the fact that the groundwater and surface water are often in close hydraulic connection, mean that the unconfined aquifers are not suited to development for river regulation. Where fractured, the limestones are highly vulnerable to pollution. The yield/drawdown relationships of the arenaceous aquifers are not generally reported separately, implying similar features. If this is so, the low storage coefficients and poor yield/drawdown performance may be more closely related to the thin beds and intercalation of fine-grained layers, which is typical of the depositional environment of marginal marine and lowland non-marine facies.

The quality of water from the Jurassic limestones is generally good but hard, with calcium and bicarbonate ions predominating. The degree of mineralisation of the water is a good indication of its age; lower total dissolved solids concentrations occur in waters that have been in the aquifer for only a short time. Downdip, beneath confining horizons, sodium replaces calcium by ion exchange and sometimes only a few kilometres from outcrop, the water becomes saline. Therefore, within the exploited part of the aquifer, the chemistry can be linked to the aquifer permeability, with good quality water indicating high permeabilities and relatively rapid movement of water through the aquifer system. Elsewhere the aquifer may still have a high fracture density, but because there is a lower throughput of water, the quality may be poor. This can make the degree of mineralisation of a given groundwater an ambiguous indicator of permeability, and it is unreliable when used in isolation from other evidence.

Models of the aquifers need to incorporate their compartmentalised nature as well as their physical properties, in order to represent their rapid response to recharge, and calibrate water levels and streamflow; they are therefore often very complex. A particular problem is the need to take into account the variable degree of cementation, which has resulted in the formation of concretionary layers and limonite-infilled joints, and an aquifer system which is irregular as well as multi-layered.

6.1.3 Aquifer properties data availability

6.1.3.1 *Core data*

Very limited porosity and intergranular permeability data from laboratory analyses of rock samples are available for the Jurassic minor aquifers. A synopsis of this information is presented in Table 6.2. Maximum, minimum, interquartile range and mean values are presented for both porosity and permeability (expressed as hydraulic conductivity). The table indicates that the data are commonly derived from a relatively small number of analyses from a limited number of sample sources. A distinction has been made between data originating from samples taken from borehole cores and those from outcrops, since the physical properties of the latter are very likely to have been modified by weathering processes.

It is noticeable that average hydraulic conductivities are typically low, often in the range 10^{-4} to 10^{-5} m/d, despite frequently high interconnected porosities (in the range 15 to 27%). For example, the mean porosity for the Corallian of the south Midlands and Kellaways Sand samples both exceed 20%, yet mean intergranular permeability in both cases was only about 10^{-4} m/d. In the absence of pore size distribution measurements (none have been conducted on onshore Jurassic core material), it is suggested that the low permeabilities in relatively porous material are due to a combination of fine grain size and the effects of cementation. Both effects would produce small pore throats with increased tortuosity, to the detriment of intergranular permeability.

6.1.3.2 *Pumping test data*

There is very limited quantitative information available for the minor Jurassic aquifers from pumping tests. Table 6.3 summarises the pumping test data, grouped by geographic area. Most of the pumping tests were carried out without observation wells and hence produced no storage coefficients. In the limestones, transmissivity values will depend on the number, nature and interconnection of the fractures encountered in the saturated zone, and therefore are likely to change depending on the time of year or initial water levels. However there are no records of sites having been tested on several occasions with significantly different initial water levels.

Table 6.2 Jurassic minor aquifers: porosity and permeability values from laboratory analyses.

Aquifer	**Sample source**		**Porosity (%)**					**Hydraulic conductivity (m/day)**				
	No. boreholes	No. outcrops	No. analyses	Interquartile range	Min.	Max.	Arithmetic mean	No. analyses	Interquartile range	Min.	Max.	Geometric mean
Purbeck	1		5	4.7 to 22.9	17.1	34.5	15.2	5	6.5×10^{-3} to 0.8	2.0×10^{-3}	1.0	6×10^{-2}
		1	4		1.0	11.7		0				
Portland Sand	1		9	9.0 to 16.9	3.3	16.2	13.2	9	3.2×10^{-6} to 1.2×10^{-4}	3.2×10^{-6}	1.8×10^{-4}	2.1×10^{-5}
		1	4		16.4	23.5		0				
Corallian (S Midlands)	1		11	6.8 to 36.2	6.0	39.3	23.7	10	5.1×10^{-5} to 1.1×10^{-3}	2.5×10^{-5}	1.4×10^{-2}	2.3×10^{-4}
Corallian (S of Mendips)		1	8	3.5 to 8.7	2.2	13.8	6.7	0				
Kellaways Sand	5		22	25.6 to 33.8	4.3	37.6	26.9	5	3.1×10^{-6} to 6.8×10^{-3}	2.8×10^{-6}	2.4×10^{-2}	3.0×10^{-4}
		1	0					1		4.4×10^{-3}	4.4×10^{-3}	
Rutland Formation	1		16	9.9 to 19.3	6.5	36.4	15.5	16	2.0×10^{-5} to 1.5×10^{-4}	3.8×10^{-6}	3.7×10^{-1}	8.7×10^{-5}
Fuller's Earth Rock	1		2		17.3	18.0	13.5	1		6.0×10^{-1}	6.0×10^{-1}	
		1	1		5.3	5.3		0				
Dyrham Formation	2		7	15.7 to 26.1	8.4	29.5	22.0	6	1.3×10^{-5} to 6.2×10^{-5}	9.0×10^{-6}	6.9×10^{-4}	3.3×10^{-5}
		2	12		12.2	31.2		9		9.4×10^{-6}	8.7×10^{-5}	
Lower Lias	3		34	5.0 to 12.5	7.1	27.5	9.4	12	3.2×10^{-6} to 3.7×10^{-3}	1.5×10^{-5}	2.8×10^{-1}	1.5×10^{-4}
		2	18		1.1	14.1		6		3.2×10^{-6}	8.3×10^{-4}	

In most cases the minor Jurassic aquifers do not meet the normal requirements for standard pumping test analysis assumptions, that is, a homogeneous aquifer of infinite areal extent. The aquifers are generally thin and leakage effects from underlying or overlying aquitards may be difficult to detect and interpret. Where large fractures are present in the limestones, non-laminar flow may occur along enlarged solution features. The combination of low storage coefficients and the compartmentalisation of the aquifers means that most pumping tests do not reach equilibrium without having been affected by boundary conditions.

Due to the very small number of pumping tests carried out on the minor Jurassic aquifers, for most producing formations the only information available for statistical analysis was specific capacity. This was used to provide some indication of the variation in potential of the different aquifers both across regions and between formations. However specific capacity is not just a function of the aquifer but is also related to the borehole diameter, well efficiency, position of the pump intake, and whether equilibrium had been reached (which is often not recorded); therefore comparisons between different locations need to be treated with caution. The specific capacity data were not corrected to a uniform diameter, as the errors caused by such variations were probably less than those caused by equilibrium not being reached. Additionally, for large diameter shallow wells, which historically were the usual means of abstraction, specific capacity is more likely to reflect the storage volume than the performance of a well. As with laboratory determinations from core samples, the few available pumping test results indicate low, but not insignificant permeabilities. Transmissivity values (which are generally less than 40 m^2/d) are likely to be limited by the thinness of the formations tested, by barrier effects, and by the complexities of local aquifer geometry. Specific capacities tend to be rather more variable, with the highest values, unsurprisingly, in the limestones, where there are likely to be karstic effects.

6.1.3.3 *Other data*

The Marlstone Rock Formation in central England is considered a locally important minor aquifer. As the original data collection exercise identified no pumping test results and only seven specific capacity values, additional yield data and information on licensed quantities were collected and analysed. Typical yields from other formations are indicated in the text.

6.1.4 General aquifer properties

As can be seen in Tables 6.2 and 6.3, there are very little data for the minor Jurassic aquifers. As a result, it is difficult to draw meaningful conclusions about their aquifer properties. In general, porosities are fairly low, with arithmetic means of usually less than 20%, as are hydraulic conductivity values (frequently between 10^{-5} and 10^{-2} m/d). Transmissivity values are also low, being generally less than 40 m^2/d. The highest transmissivity values of 700 and 426 m^2/d, obtained from the Corallian and Blue Lias respectively, are considered to be highly atypical, being an order of magnitude higher than those obtained from any of the other Jurassic aquifers covered by this chapter. Storage coefficients are very variable, reflecting both confined and unconfined conditions.

6.2 CLEVELAND BASIN

6.2.1 Introduction

The Cleveland Basin described below is the area of Jurassic rocks north of the Market Weighton Axis. The rocks crop

Table 6.3 Jurassic minor aquifers: physical properties from pumping tests.

Area	Aquifer	Transmissivity (m^2/day)						Storage coefficient				Specific capacity (m^3/d/m)					
		No. values	No. sites	Interquartile range	Min.	Max.	Geometric mean	No. values	No. sites	Min.	Max. values	No. sites	No.	Interquartile range	Min.	Max.	Geometric mean
Cleveland Basin	Ravenscar (Scalby Formation Group (Cloughton Fm	1 0	1		17	17		0 0				3 1	3 1		0.4 57	22 57	4.8
	Staithes Formation	0						0				4	2		3.5	4.2	
	Redcar Mudstone Formation	1	1		1.4	1.4		0				12	9	17.2 to 54.3	1.2	193	23.8
South of Market Weighton	Portland Group	0						0				6	4	2.8 to 449	1.9	879	46.8
	Elsham Sandstone Formation	5	2	6.9 to 25.5	4.0	29.0	14.4	3	2	3.5×10^{-6}	2×10^{-4}	1	1		8.5	8.5	
	Corallian (S Midlands)	2	1		695	700	695	2	1	5.7×10^{-4}	6.2×10^{-4}	35	29	17.3 to 186	4.2	2177	54
	Corallian (S of Mendips)	3	3		1.0	21.0	4.6	0				6	5	2.0 to 27.5	0.95	109	8.5
	Cornbrash	0	0					0				1	1		10.9	10.9	
	Forest Marble	3	3		2.0	35.3	12.1	2	2	1.0×10^{-3}	0.16	5	4	9.2 to 87.7	8.6	115	26.6
	Marlstone Rock	0						0				7	7	13 to 497	7.2	1000	76.7
	Dyrham Formation	2	2		3.0	50	12.2	0				4	4		13.3	201	66.1
	Frodingham Ironstone	1	1		0.2	0.2		0				1	1		1.3	1.3	
	Lower Lias	19	16	9.0 to 39	2.0	426	20.4	7	6	1.5×10^{-4}	0.15	26	23	6.6 to 38	0.13	920	15.3

Table 6.4 The Jurassic sequence of the Cleveland Basin.

	Kimmeridge Clay Formation	up to 385 m mudstones (often calcareous) and oil shales
	Ampthill Clay Formation	45–50 m
	CORALLIAN GROUP	100–150 m calcareous sandstones and limestones
	Oxford Clay	up to 35 m
	Osgodby Formation	*Hackness Rock Member* 2 m calcareous sandstone with interbedded limestones *Langdale Member* 2–15 m sandstone *Redcliff Rock Member* (formerly *Kellaways Rock*) 7–16 m chamositic sandstone
	Cornbrash Formation	Upper Cornbrash shale up to 3 m up to 3.5 m limestone (sandy in west, shelly in east)
Ravenscar Group (210 m)	**Scalby Formation** (formerly Upper Deltaic Series)	40–90 m mudstones, siltstones and sandstones
	Scarborough Formation	up to 32 m limestone, sandstone and shale
	Cloughton Formation (formerly Middle Deltaic Series)	70 m shales, sandstones and subordinate limestones
	Eller Beck Formation	4.5–8 m shales and ironstones overlain by shaly sandstone
	Saltwick Formation (formerly Lower Deltaic series)	45 m sandstone and shale
	Dogger Formation	up to 13 m chamositic sandstone
Lias Group	**Blea Wyke Sandstone Formation**	up to 18 m
	Whitby Mudstone Formation (formerly Upper Lias)	up to 105 m mudstone and shale with sandstone beds
	Cleveland Ironstone Formation	up to 25 m mudstone and siltstone with beds of oolitic ironstone
	Staithes Sandstone Formation	up to 30 m micaceous, calcareous sandstone and sandy siltstone
	Redcar Mudstone Formation (formerly Lower Lias)	up to 285 m mudstones and siltstones with subsidiary thin limestones, sandstones and ironstones

CAPITALS = main aquifers
Bold = other aquifers

out over the Cleveland Hills, Hambleton Hills, Howardian Hills and North Yorkshire Moors and underlie superficial deposits in the Vale of Pickering. As elsewhere, the Lower Jurassic sequence is predominantly shales and clays alternating with limestones, ironstones, siltstones and sandstones; however, the Middle Jurassic comprises a thick sequence of fluvial, estuarine and deltaic beds (Dogger Formation and Ravenscar Group) and the Upper Jurassic includes alternating marine calcareous shales and oolitic limestones (Corallian Group) overlain by clays (Ampthill and Kimmeridge clays).

6.2.2 Geology and stratigraphy

The sequence is summarised in Table 6.4. The deposits reach a maximum thickness of around 1100 m. The outcrop patterns are relatively complex due to the faulted and gently folded nature of the sediments. The principal aquifer within the area is the Corallian Group, described in Allen et al. (1997); it is not discussed further here. However, there are also several minor aquifers including the Staithes Sandstone Formation, Cleveland Ironstone Formation, Dogger Formation, Ravenscar Group, Osgodby Formation as well as permeable limestone and sandstone horizons within the low permeability mudstone sequences. The outcrop of the Lias and the Ravenscar Groups and the distribution of all the sites in these aquifers with pumping test and specific capacity data are shown in Figure 6.3.

6.2.2.1 *Redcar Mudstone Formation*

The Redcar Mudstone Formation is predominantly argillaceous, with thin limestone bands in the Calcareous Shales. These contain some water.

6.2.2.2 *Staithes Sandstone Formation*

This is a substantial unit of fine- to medium-grained marine sandstone; often micaceous, with a calcareous cement and lenses of ironstone. It is up to 30 m thick in the north of the crop (Saltburn area), typically 20 m thick between Staithes and the Hambleton Hills, but thins farther south with the development of shales and ironstone.

6.2.2.3 *Cleveland Ironstone Formation*

This formation comprises a succession of mudstones, siltstones and ironstones; typically of the order of 20 m thick, reaching a maximum of 24 m in the north (Guisborough area, near Middlesborough) and thinning out to almost nothing south-east of Thirsk. There are six main ironstone seams, generally 0.5 to 1 m thick. These were worked along the northern crop between Guisborough and the coast until 1964, generally by underground adits and latterly by longwall methods. Therefore although the formation is essentially an argillaceous non-aquifer, mining and associated collapse will have had an effect on groundwater flow. In the Northallerton district the Cleveland Ironstone Formation gives rise to significant springs (Frost, 1998).

6.2.2.4 *Blea Wyke Sandstone Formation*

On the coast this formation comprises about 20 m of fine-grained sandstones, rather argillaceous in the lower part (‘Grey Beds’), less so in the upper part (‘Yellow Beds’). It thins inland, possibly becoming less sandy and locally includes oolitic ironstones (Rosedale area). It is lithologically similar to the Staithes Sandstone Formation, and is only of limited significance as an aquifer.

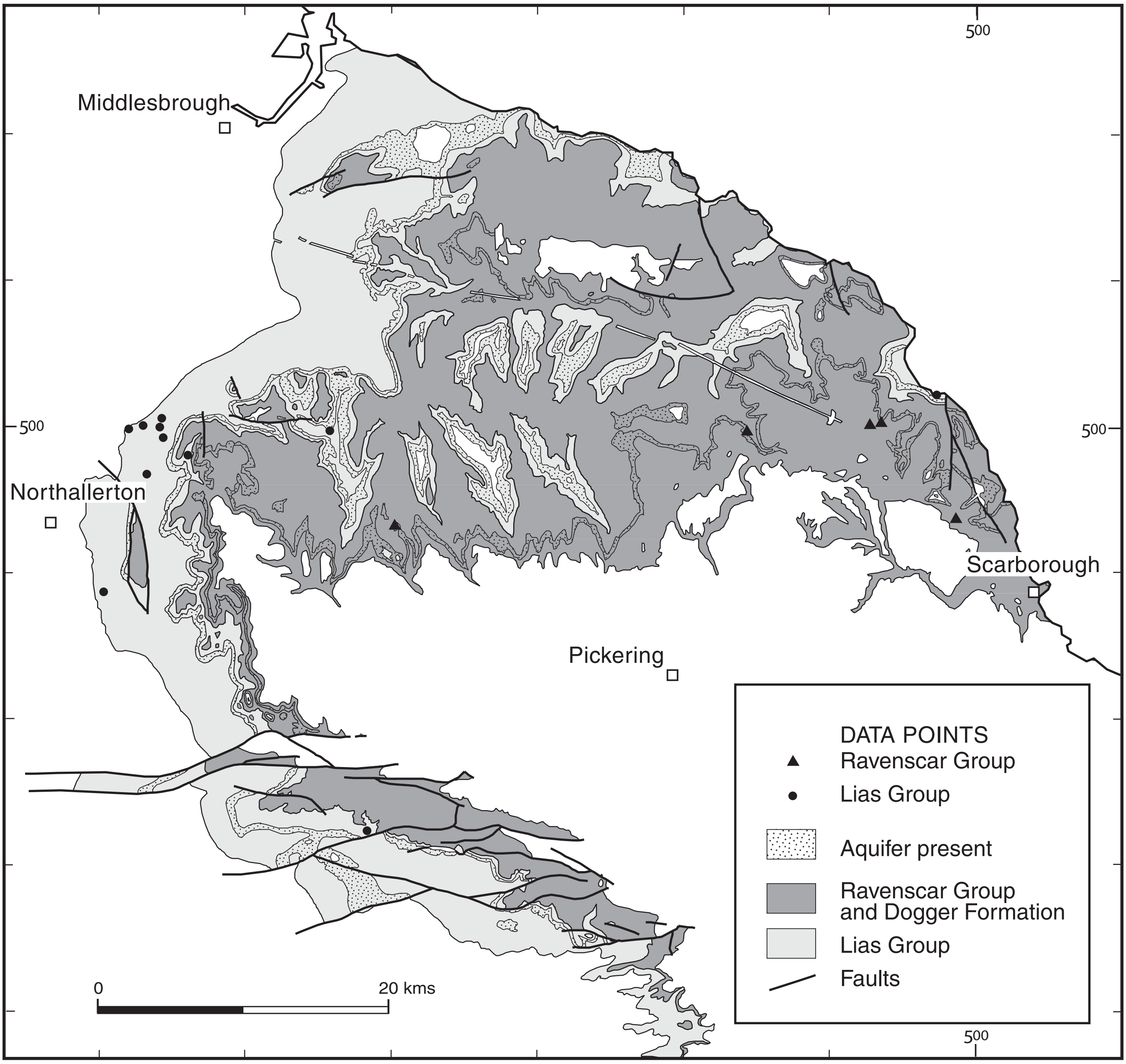

Figure 6.3 Outcrop of, and distribution of sites in, the Lias and Ravenscar groups north of York.

6.2.2.5 *Dogger Formation*

The Dogger Formation is a very variable unit, up to 13 m thick but typically only 3 to 4 m; it is locally cut out by the overlying Saltwick Formation of the Ravenscar Group. On the coast, it is made up predominantly of ferruginous sandstones with local developments of oolitic ironstone; the latter are present particularly in the north. Generally a basal conglomerate is present which rests on an eroded Blea Wyke Sandstone surface. Inland, on the western scarp of the moors, it includes bioclastic limestones and mudstone intercalations all ferruginous to some extent, and also the very local and formerly worked 'Magnetite Ironstone' of Rosedale.

6.2.2.6 *Ravenscar Group*

The Ravenscar Group comprises a thick sequence of coastal, fluvial and estuarine sediments, typically about 210 m thick; it corresponds to the former Estuarine or Deltaic Series. Together with the Dogger Formation, the group's extensive outcrop forms all but the southern (Corallian) part of the Cleveland Hills and North Yorkshire Moors, and also the Howardian Hills between Malton and Thirsk. The northern part of the outcrop is concealed beneath glacial drift. The group forms cliffs along the coast between Scarborough and Blea Wyke and intermittently farther north, and is present at depth to the south beneath the Vale of Pickering.

The Ravenscar Group and Dogger Formation can be divided into six formations, due to the intercalation of three marine units (Dogger, Eller Beck and Scarborough formations) within an essentially non-marine succession. The sequence from the top is:

Scalby Formation	up to 90m thick
Scarborough Formation	about 25 m thick
Cloughton Formation (with Lebberston Member)	about 70 m thick
Eller Beck Formation	about 5 m thick
Saltwick Formation	about 45 m thick
Dogger Formation	0 to 13 m thick

Saltwick Formation

The Saltwick Formation is dominantly made up of mudstones, siltstones and argillaceous sandstones with thin ironstones. Parts of the sequence contain delta-type cycles similar to the Coal Measures, with the development of rootlet beds and thin low-grade coaly horizons. The latter were worked locally in the past. The formation contains major quartzo-feldspathic sandstones that may be up to 20 m thick, but are more usually only 2 to 8 m. Together with the Cloughton Formation, this formation includes the coarsest grade sediments of the group, and they jointly comprise the principal aquifers. However, because of their origin as fluvial or delta distributary channels they have a complex and largely unpredictable three dimensional geometry and may divide laterally, be split by mudstone intercalations, or cut down into, and connect with, other sandstone aquifers.

Eller Beck Formation

This is typically 4 to 6 m thick, but reaches 8.2 m in the north-west. It comprises a basal shale with ironstones overlain by medium to fine-grained sandstones which make up the greater part of the formation (up to 6 m thick). It was deposited during a basinwide marine transgression, therefore the sandstone is a persistent ‘planar’ body unlike the channel sandstones of the non-marine parts of the Ravenscar Group.

Cloughton Formation (with Lebberston Member)

Lithologically, the Cloughton Formation is very similar to the Saltwick Formation. The low grade coaly horizons that have been described under the Saltwick Formation are better developed in this formation, and include rare seams up to 0.5 m thick.

The Cloughton Formation is divided into two by the median Lebberston Member (1 to 8 m), another marine interlude. It is composed of calcareous sandstones and a sandy oolitic limestone, the Millepore Bed of the coast and the Whitwell Oolite of the Hambleton and Howardian Hills. It can reach 8 m in thickness at outcrop but is usually rather less; it may be thicker at depth, in the south, beneath the Vale of Pickering.

Scarborough Formation

The Scarborough Formation is of variable lithology, comprising shales, calcareous sandstones and sandy limestones with ironstones. In the Howardian Hills, and along the western scarp of the moors, it includes the Crinoid Grit, a coarse locally conglomeratic sandstone, up to 12.5 m thick, often decalcified and highly porous (at outcrop at least). The formation reaches a maximum thickness of 32 m at Ravenscar where it includes substantial sandstone units but thins rapidly southwards to only 2 m, where the sandstone also tends to be less dominant. Large springs of hard water issue from the base of the porous, gravelly Crinoid Grit (e.g. Newfield House on Snilesworth Moor).

Scalby Formation

The Scalby Formation is typically about 65 m thick, perhaps up to 90 m in places. It thins to only about 40 m just north of Scarborough. The upper and greater part of the formation (Long Nab Member) comprises mudstones and siltstones with minor channel sandstones, particularly towards the base. However, the lower part of the formation is made up of major, extensive fluvial sandstones which are important for water supply. The Moor Grit, up to 20 m thick, the only non-marine sandstone in the Ravenscar Group to have been separately named, rests with a major non-sequence on the underlying Scarborough Formation (perhaps accounting for some of the thickness variation of the latter). It is persistent, generally highly siliceous and may be re-cemented into a quartzite in places.

6.2.2.7 *Cornbrash Formation*

This typically comprises about 1 m of rubbly, rather sandy limestone, but may reach up to 3.5 m in thickness locally. It is very thin, but probably not absent, in the west of the outcrop area from Scarborough across the southern part of the moors into the Hambleton Hills. It rests on the argillaceous upper part of the Scalby Formation and is succeeded by the Cayton Clay (formerly ‘Shales of the Cornbrash’).

6.2.2.8 *Osgodby Formation*

This sandstone dominated unit, equivalent in age to the Kellaways Formation and Lower Oxford Clay of the rest of England, is divided into three members, all essentially sandstone, separated by erosive non-sequences. The total thickness is rather variable, but 20 to 25 m is fairly typical. The sequence from the top downwards is:

Hackness Rock Member: typically 2 m of fine-grained sandstones and thin limestones.

Langdale Member: up to 15 m of fine-grained sandstones with thin clay partings. It is cut out very locally on the coast just south of Scarborough.

Redcliff Rock Member (formerly Kellaways Rock): fine-grained calcareous sandstone with hard concretions. It is up to 16 m thick inland, but only 10 or 12 m on the coast and is cut out by the succeeding Langdale Member just south of Scarborough.

6.2.3 Hydrogeology

6.2.3.1 *Redcar Mudstone Formation*

As stated in Section 6.2.2.1, although the Redcar Mudstone Formation is predominantly argillaceous, thin limestone bands in the Calcareous shales may contain some water.

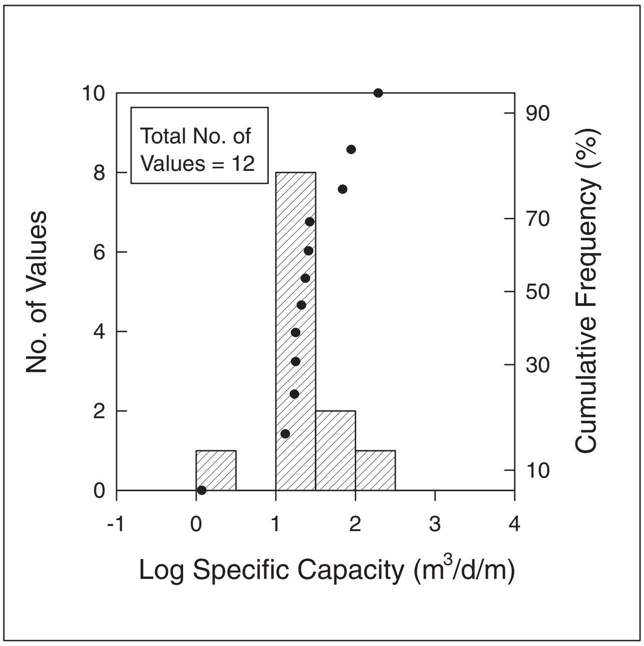

Figure 6.4 Distribution of specific capacity values for the Redcar Mudstone Formation.

The overlying sandy shales yield 40 to 174 m^3/d in the Northallerton district (Frost, 1998).

In the database there are 12 values of specific capacity from nine sites; their distribution is shown in Figure 6.4. Values vary from 1.2 to 193 m^3/d/m with a geometric mean of 24 m^3/d/m. The highest value is from a 30 m deep borehole, pumped at 216 m^3/d at the Cleveland Tontine Inn [SE 4439 9930]. There is one value of transmissivity for a site at Low Peak Farm [NZ 974 021]; 1.4 m^2/d from a constant rate test of 24 hours duration.

6.2.3.2 *Staithes Sandstone Formation*

Its generally fine grainsize and tight cementation suggest the Staithes Sandstone Formation forms a less significant aquifer than the Ravenscar sandstones: however it is utilised for water in the Thirsk district (Powell et al., 1992) and significant springs issue from the formation in the Northallerton district (Frost, 1998).

There are four values of specific capacity from two locations; Cote Ghyll Youth Hostel [SE 4614 9811] with a mean value of 4.1 m^3/d/m and Mill Farm [SE 5838 7233] with a value of 3.5 m^3/d/m The aquifer for this second site is unknown but is probably the Staithes Sandstone Formation beneath the Whitby Mudstone and Cleveland Ironstone formations.

6.2.3.3 *Ravenscar Group*

The sandstones and limestones of the Ravenscar Group have some potential as aquifers, although groundwater flow is restricted by the numerous, interbedded, thin mudstone aquitards. East of Thirsk, the outcrop is limited and there are only a few shallow wells used for domestic supplies. Further north in the Cleveland Hills and on the North Yorkshire Moors it is used more.

Saltwick and Cloughton formations

A multitude of springs issue from these sandstones, some of which form the headwaters of the River Rye. Northumbria Water is licensed to abstract 265 485 m^3/a from a group of five springs at Scugdale (of which three [at SE 508 995, SE 497 997 and SE 517 992] issue from the Cloughton and Saltwick formations) and 80 000 m^3/a from a spring at Kildale [NZ 517 022] from the Cloughton Formation. Colour, quality and taste variations mean that the water does not meet EC standards without expensive treatment; these sources are therefore no longer used for public supply.

Near the coast between Whitby and Scarborough, the predominantly sandstone succession is covered by impermeable clay, limiting recharge. Small supplies are usually obtainable from the sandstones from springs or wells sunk through drift. A boring at Raven Hill [NZ 8628 1220] which was sited on the edge of a buried valley and penetrated 25.6 m of glacial drift over Whitby Mudstone, obtained most of its water from 'ballast' at the base of the drift which probably collects some of the water from the overlying Dogger and Saltwick formations which subcrop just up the hill from the borehole (Fox-Strangways and Barrow, 1915). The sandstones reach their greatest depth below sea level in the Esk valley, a mile south of Whitby, close to the Whitby fault. A boring at Ruswarp [NZ 890 090], made in 1821, penetrated 6.7 m of alluvium over 66.9 m of Ravenscar Formation before reaching the Dogger. Fox-Strangways and Barrow (1915) thought it possible that a large amount of fresh water could be obtained from this borehole, if the brackish water from the estuary was cased out from the upper part, as a shaft sunk in a similar structural position at North Skelton, near Saltburn [NZ 673 182] met with abundant water. However, this shaft is further north where there are more sandstones, the beds are also more persistent and less lenticular and therefore the recharge area is larger.

Alexander and Gawthorpe (1993) studied the sedimentology and permeability of the 25 m thick complex, multistorey sandstones of the Saltwick Formation adjacent to a fault at Whitby. Similar vertically stacked channel sandstones have been observed in the hanging walls of other faults in the Cleveland Basin (e.g. at Ravenscar) (Alexander, 1986). At Whitby the pore space was reduced and the pore tortuosity increased by compaction and diagenesis when the sandstone was buried to a depth of about 2 km. Permeability ranges from 0.8 to 682 mD (3.3×10^{-4} to 4.2×10^{-1} m/d) with a geometric mean of 83.5 mD (4.5×10^{-2} m/d). The cross-bedded sandstones generally have both higher permeabilities and greater variations in permeability than other facies. Where the sandstones are tightly cemented with siderite, the permeabilities are an order of magnitude lower than elsewhere. Alexander and Gawthorpe (1993) concluded that although permeability is strongly related to sedimentary facies, there are variations (of the order of a factor of 2 or 3) between sandstones of the same genetic type that cannot be explained by variations in facies percentages or the burial and diagenetic history.

There is one value of specific capacity for the Cloughton Formation at Sadler House Farm [SE 8439 9980], this is 57 m^3/d/m.

Scalby Formation

The Scalby Formation includes the Long Nab Member and underlying Moor Grit. The Moor Grit, although bedded in wedges has no impermeable partings between the wedges and hence behaves as one aquifer. At the junction with the underlying less permeable shales of the Scarborough Formation, numerous springs are thrown out. In the immediate vicinity of Whitby its outcrop is mostly buried under till, so recharge is limited. Further south its outcrop often occurs at the foot of the long slope formed by the overlying low permeability Long Nab Member, so much of the rainfall falling on the latter flows down into the Grit and issues as springs along the sides of the valleys, as in Iburndale, and the area west of Robin Hood’s Bay. The water supply of Robin's Hood Bay, although abstracted from the glacial sands at Kirk Moor Gate [NZ 91 92], was possibly partially derived from the Moor Grit, as water issuing from the Grit probably passes into the sands (Fox-Strangways and Barrow, 1915). In the area south of Robin Hood’s Bay there are numerous springs from the Moor Grit, but none of large volume. Further west a large spring issues from faulted Moor Grit above Osmotherley, forming the source of the Cod Beck. Water from the Moor Grit is soft.

There is one value of transmissivity from the Moor Grit on East Moors near Piethorne [SE 603 934] of 17 m^2/d. A 30 m deep well, at Fair Hill Farm, Hawnby [SE 5610 8934], in the Scalby Formation, yielded 130 m^3/d for two days for no measurable drawdown. Otherwise the three values of specific capacity from the Scalby Formation range from 0.4 to 22.1 m^3/d/m, with a geometric mean of 5 m^3/d/m.

6.2.3.4 *Osgodby Formation*

The lowermost Redcliff Rock Member (formerly Kellaways Rock) is remarkably porous and covers an extensive area in the south-west of the Whitby and Scarborough districts. As its surface is drift free, a considerable volume of water enters this bed and emerges as springs along its southern margin or down dip. Its jagged southern outcrop pattern is due to the streams from these springs eating their way back into the outcrop. Downdip it is confined by the Oxford Clay.

An 87 m long adit on Kepwick Moor [SE 487 919] which encountered water at a distance of 80 m into the Redcliff Rock Member had a discharge of 2250 m^3/d in 1924 (Frost, 1998). Yorkshire Water is licensed to abstract 1 272 900 m^3/a from this adit and 15 springs in the surrounding area of the Cleveland Hills. These springs mainly issue from the base of the Osgodby Formation and associated landslips, but a few are from the Moor Grit or the Corallian.

In the Vale of Pickering around Ampleforth the formation is used for local agricultural supplies, and is locally highly artesian.

6.3 SOUTH OF MARKET WEIGHTON

6.3.1 Introduction

This section covers all the Jurassic south of Market Weighton and includes the East Midlands Shelf, the Worcester Basin and Cotswolds, and the Wessex Basin. The geology is quite distinct from that of the Cleveland Basin. The three depositional basins used to subdivide the major aquifers of the Jurassic in Allen et al. (1997) are less important in terms of the Jurassic minor aquifers. This is because the latter tended to be deposited at the edges of basins, and sometimes continued over the structural highs; some of the aquifers therefore occur across much of the country, and cannot conveniently be allocated to distinct basins.

The three main depositional areas are summarised below, although as explained above, it should be noted that the minor aquifers are not always restricted to these areas.

East Midlands Shelf

The East Midlands Shelf covers the area between the Market Weighton and Vale of Moreton highs (see Figure 6.1). The outcrop of Jurassic rocks broadens from Market Weighton southwards across Lincolnshire into the Midlands. The straight outcrop in the north reflects the gentle eastwards tilting at 1–2°, but otherwise almost completely unfolded nature of the rocks. The rocks thicken progressively southwards and, because of the decreasing overstep by the Cretaceous, the outcrop broadens. South of Peterborough the dip becomes south-easterly.

The generalised succession is shown in Table 6.5. Northwards from the Humber estuary the increased Cretaceous overstep of the Jurassic progressively truncates the latter's outcrop, such that only the Lias is present at outcrop near Market Weighton. At the Humber the Lias, Grantham Formation, Lincolnshire Limestone, Rutland Formation (which is sandy in this area), Blisworth Clay, Cornbrash, Kellaways Formation, Oxford Clay, West Walton Formation, Ampthill Clay and Kimmeridge Clay are present and the Northampton Sand and Blisworth Limestone are absent. The Grantham Formation and Blisworth Clay have also disappeared by North Cave. South of the Humber estuary the whole Jurassic succession from the Lower Lias to the Spilsby Sandstone is present.

The principal aquifers of the area are the Lincolnshire Limestone (discussed in Allen et al., 1997) and the Spilsby Sandstone (which crosses the Jurassic–Cretaceous boundary, and is discussed in Chapter 5). The minor aquifers described here include the Frodingham Ironstone (Scunthorpe Mudstone Formation), Dyrham Formation, Marlstone Rock Formation, Northampton Sand Formation, Blisworth Limestone Formation, Cornbrash Formation, Kellaways Sand, parts of the Corallian and the Portland beds as well as the

Table 6.5 The Jurassic sequence on the East Midlands Shelf.

	SPILSBY SANDSTONE (lower part)	up to 25 m glauconitic sandstone
	Kimmeridge Clay Formation	up to 180 m mudstones with thin argillaceous limestones and oil shales
	Ampthill Clay Formation	up to 100 m silty mudstones
	West Walton Formation	up to 25 m siltstones and muddy limestones
	Oxford Clay Formation	up to 120 m calcareous mudstones
	Kellaways Formation	**Kellaways Sand Member** up to 8 m Kellaways Clay Member up to 4 m
Great Oolite Group	**Cornbrash Formation**	up to 6 m shelly limestones with marly and sandy partings
	Blisworth Clay Formation (formerly Great Oolite clay)	up to 10 m clay
	Blisworth Limestone Formation (formerly Great Oolite limestone)	up to 8 m limestone
	Rutland Formation (formerly Upper Estuarine Series)	up to 20 m sands, silts and clay
Inferior Oolite Group	LINCOLNSHIRE LIMESTONE FORMATION	up to 40 m limestone
	Grantham Formation (formerly Lower Estuarine Series)	up to 8 m sands, silts and clays
	Northampton Sand Formation	up to 20 m ferruginous sandstone
Lias Group	Whitby Mudstone Formation	up to 55 m mudstones and shales
	Marlstone Rock Formation	up to 10 m calcareous ironstone
	Dyrham Formation	up to 25 m
	Charmouth Mudstone Formation	up to 115 m calcareous mudstones and shales
	Scunthorpe Mudstone Formation (north)	**Frodingham Ironstone** up to 10 m calcareous ironstone
	Blue Lias Formation (south)	up to 130 m mudstones with thin limestone

CAPITALS = main aquifers
Bold = other aquifers

continuation south-westwards from Kettering of the Lincolnshire Limestone/Inferior Oolite aquifer.

The aquifers are normally separated by siltstones and mudstones, although hydraulic continuity is common. For example, north of Brough, all the formations from the Kellaways Rock to the Lincolnshire Limestone act as one aquifer. Similarly south of the Humber, the Northampton Sand and Lincolnshire Limestone are in hydraulic continuity wherever the Grantham Formation is incomplete or absent. Faulting, particularly north of the Humber, complicates hydraulic relationships, sometimes forming barriers and sometimes connecting aquifers.

The Cotswolds/Worcester Basin

This is the area between the Vale of Moreton and the Mendips axes. The sequence is summarised in Table 6.6. The principal aquifers within this area are the Upper Lias Sands, Inferior Oolite and Great Oolite Group, which are described in Allen et al. (1997). The minor aquifers described here are the Blue Lias, Dyrham Formation, Marlstone Rock Formation, Junction Bed, Fuller's Earth Rock, Cornbrash Formation, Corallian Group, and Portland and Purbeck groups.

Richardson (1946) was the first person to describe the aquifers of the Cotswolds and the interconnection between them and the springs and streams. This was followed in the seventies by a series of theses describing the hydrogeology of various surface water catchments. Reed (1975) studied the Windrush and Leach catchments, Al-Dabbagh (1975) the Coln, Churn and Frome catchments and Bromley (1975) the Bristol Avon in the south Cotswolds. Although all of these studies concentrate on the major aquifers, most contain small amounts of data on the less important aquifers.

Wessex Basin (including Bristol Channel–Central Somerset)

This covers the Jurassic in the area between the Mendips and the south coast. A nearly complete Jurassic sequence, about 1350 m thick, is present and exposed along the Dorset coast between Lyme Regis and Swanage. The generalised succession is shown in Table 6.7. The main aquifers in this area are the Junction Bed, Upper Lias Sands, Inferior Oolite, Osmington Oolite (part of the Corallian Group) and the Portland Stone described in Allen et al. (1997). The less important aquifers described here are the Blue Lias, Dyrham Formation (formerly Pennard Sand Formation), Fuller's

Table 6.6 The Jurassic sequence of the Worcester Basin/Cotswolds.

	Purbeck Group	up to 7 m limestones and marls	
	Portland Group	up to 13 m sands and limestones	
	Kimmeridge Clay Formation	up to 100 m mudstones	
	Corallian Group	25 to 35 m sandstones, clays, bioclastic limestones	
	Oxford Clay Formation	up to 150 m mudstones	
	Kellaways Formation	**Kellaways Sand Member** up to 4 m Kellaways Clay Member up to 28 m	
GREAT OOLITE GROUP	**Cornbrash Formation**	up to 5 m shelly limestone	
	FOREST MARBLE FORMATION	up to 35 m limestones and clays	
	SOUTH-WEST	**CHIPPENHAM**	**NORTH-EAST**
	GREAT OOLITE FORMATION 20–30 m		
	Upper Fuller's Earth Formation up to 28 m	ATHELSTAN OOLITE up to 25 m	WHITE LIMESTONE FM 20 m
		TRESHAM ROCK up to 18 m	
		Hawkesbury Clay up to 10 m	
	Fuller's Earth Rock Formation up to 5 m		
	Lower Fuller's Earth Formation 10–15 m		Hampen Formation up to 10 m
			TAYNTON LIMESTONE FORMATION up to 12 m
			Fuller's Earth/Sharp's Hill Formation up to 25 m
			CHIPPING NORTON LIMESTONE FORMATION up to 12 m
	INFERIOR OOLITE GROUP	10–110 m oolitic limestone	
Lias Group	BRIDPORT SAND FORMATION (formerly Cotteswold/Midford Sands)	up to 75 m friable sandstones	
	Whitby Mudstone Formation	up to 80 m mudstones	
	Junction Bed	up to 1.5 m limestones and marls	
	Marlstone Rock Formation	up to 7 m ferruginous sandy limestone	
	Dyrham Siltstone Formation	up to 50 m sandy siltstone	
	Charmouth Mudstone Formation	200 m mudstones	
	Blue Lias Formation	up to 100 m mudstones with limestone bands	

CAPITALS = main aquifers
Bold = other aquifers

Earth Rock, Forest Marble Formation, Cornbrash, Corallian (except for the Osmington Oolite of Dorset), Portland Sands and Lulworth Formation of the Lower Purbeck.

6.3.2 Geology and stratigraphy

6.3.2.1 *Blue Lias Formation and equivalents*

The Blue Lias Formation is the basal, more permeable part of the Lower Lias, overlying the 'White Lias' of the Penarth Group (Triassic in age). Across much of England, the formation is lithologically similar; however, the marginal facies of the Mendips and Wales are quite distinct from the rest of England, and are discussed separately below.

England

In the north-east, the Blue Lias Formation becomes the Scunthorpe Mudstone Formation (see Section 6.3.2.2). In the Cleveland Basin, the equivalent is the Redcar Mudstone Formation. The outcrop of, and distribution of sites with pumping test data in, the Lower Lias are shown in Figure 6.5. Over the majority of England, it typically consists of thin (0.1 to 0.3 m thick) but laterally very persistent limestones with intervening mudstones. These thin, but well-jointed, limestones form a multi-layered minor aquifer.

The Blue Lias Formation reaches a maximum thickness of 55 to 60 m in the centre of the Worcester Basin. It is absent at the Vale of Moreton High and thins southwards to about 20 m at Dundry (Green, 1992). In the Wessex Basin area, the formation is 26 m thick on the Dorset coast, where the limestones comprise nearly half this thickness; it reaches perhaps 140 m in west Somerset and along the Somerset coast, due to the development of thicker mudstone interbeds and some major mudstone units at the base.

Wales

The Blue Lias in Wales is lithologically quite distinct from other areas; it is known as the St Mary's Well Bay Formation, and is overlain by the Lavernock Shales and Porthkerry Formation. In south Wales the Blue Lias generally comprises up to 150 m of relatively impermeable thinly interbedded limestones and mudstones. These pass laterally into marginal facies, containing coarse bioclastic limestones and limestone-chip conglomerates, which rest unconformably on older rocks. The marginal facies generally fringe the Dinantian limestones of the Cardiff–Cowbridge anticline, but in places overlie Triassic rocks and are locally interbedded with the Blue Lias (Wilson et al., 1990). Around Southerndown [SS 88 74], they are locally called the Sutton Stone

Table 6.7 The Jurassic sequence in the Wessex Basin.

Purbeck Group	**Lulworth Formation** (Lower Purbeck)	up to 60 m laminated limestones with evaporites at base
Portland Group	PORTLAND LIMESTONE FORMATION	up to 50 m sandy, shelly limestones
	Portland Sand Formation	up to 50 m sandy dolomite underlain by silty clay
	Kimmeridge Clay Formation	up to 500 m clays and shales
Corallian Group	**Corallian Group**	up to 90 m limestones, grits and clays, includes OSMINGTON OOLITE
	Oxford Clay Formation	up to 150 m clays and shales
	Kellaways Formation	
	Kellaways Sand Member	up to 4.5 m
	Kellaways Clay Member	up to 21.0 m
Great Oolite Group	**Cornbrash Formation**	up to 12 m limestone and sandy marl
	Forest Marble Formation	up to 55 m clays with thin sandstones and thin central limestones
	Frome Clay	up to 60 m calcareous mudstones with Wattonensis Beds (up to 8 m argillaceous limestones) at base
	Upper Fuller's Earth	8–15 m calcareous mudstones and thin limestones
	Fuller's Earth Rock	4–10 m rubbly limestone
	Lower Fuller's Earth	35–55 m mudstones with thin limestones
	INFERIOR OOLITE GROUP	2–120 m limestone
	INLAND	**DORSET COAST**
Lias Group	YEOVIL SANDS — up to 90 m sands with local limestones	BRIDPORT SANDS – up to 120 m sands Downcliff Clay – up to 21 m
	LIMESTONE up to 6 m MARLSTONE ROCK FORMATION up to 6 m	LIMESTONE up to 1.5 m MARLSTONE ROCK FORMATION 0.2–4.3 m JUNCTION BED
	Dyrham Formation/Pennard Sands Formation up to 72 m	**Thorncombe Sands** – up to 28 m yellow sands
		Downcliff Sands – 27 m micaceous sands and clays with sandstone bands and ironstone nodules
		Eype Clays 60 m
		Green Ammonite Bed – 30 m clays
	Charmouth Mudstone Formation, up to 230 m mudstones, shales	Belemnite Marls – 23 m calcareous marls
		Black Ven Marls – 43 m shales with impersistent limestones
		Shales with Beef – 22 m shales with mudstones and seams of fibrous calcite
	Blue Lias up to 140 m interbedded lst	**Blue Lias** – 26 m mudstones and shales with limestone bands and shales

CAPITALS = main aquifers
Bold = other aquifers

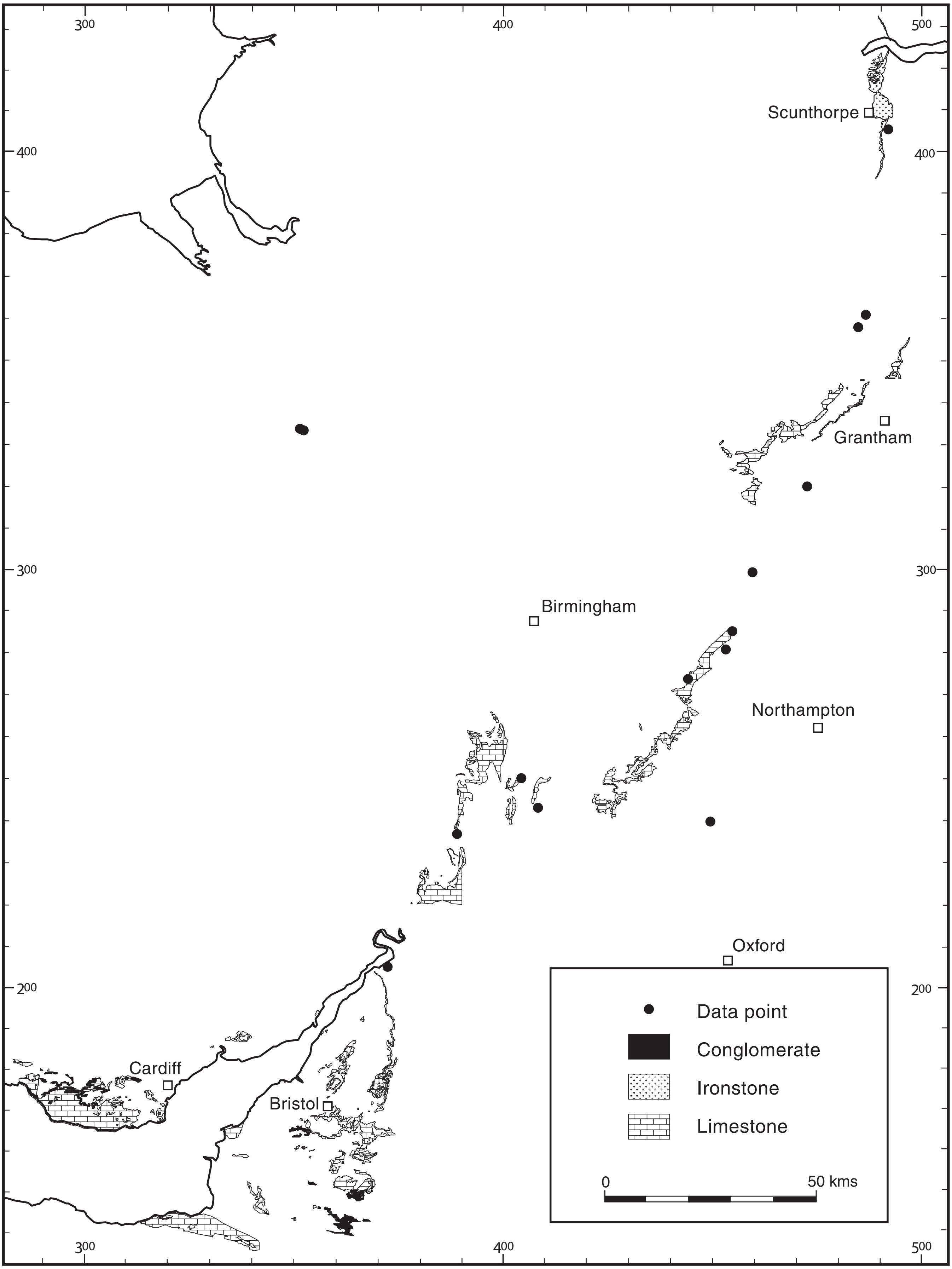

Figure 6.5 Outcrop of, and distribution of sites with pumping test data in, the Lower Lias.

and Southerndown Beds. (Fletcher et al., 1986; Fletcher, 1988). The Southerndown Beds include conglomerates, coquinoid (coarse, clastic, shelly) limestones, cross-bedded detrital limestones and oolites. Other marginal facies occur in the area around Bridgend and Cowbridge. Their thickness and extent is limited but where present these beds form potential aquifers. Further east the marginal facies to the north of St. Fagans [ST 12 78] is unlikely to be of importance due to its small outcrop area (Waters and Lawrence, 1987).

Mendips

The Blue Lias is very thin again in the Mendips area, where it often comprises an atypical marginal facies which is not strictly Blue Lias, represented by 15 to 30 m of massive limestones known as the Downside Stone.

6.3.2.2 *Frodingham Ironstone*

The Frodingham Ironstone is the uppermost member of the Scunthorpe Mudstone Formation. It is restricted to the area around Scunthorpe (where it is up to 10 m thick) and northwards to the Humber estuary. The Scunthorpe Mudstone is equivalent to the Blue Lias Formation and the lower part of the Charmouth Mudstone Formation further south, and is the lowest Jurassic formation present in Lincolnshire. The ironstone is both overlain and underlain by mudstones. It thins, becoming less ferruginous and more calcareous, very rapidly to both the north and south of this area, but possibly continues at depth as far east as Grimsby. Where fresh it is greenish grey in colour, but at outcrop it is pervasively weathered and oxidized. It was worked extensively for ironstone in the past and large areas of the outcrop have been quarried away. Significant dewatering still takes place from mine-workings in the Scunthorpe area. Quarrying ceased in 1988 and many workings are now restored or built on; however, they have implications for groundwater pollution.

6.3.2.3 *Dyrham Formation*

The Dyrham Formation, formerly the Middle Lias silts and clays, comprises muddy, fine-grained sands and sandy mudstones. It is present from Grantham southwards to the Dorset coast (Figure 6.6).

The Dyrham Formation occurs across the southern half of the East Midlands Shelf. It varies from 36 m thick at Grantham to 9 m at Banbury. In the Cotswolds type area, the formation comprises fine-grained sands and silts, varying in thickness from 20 m at Dyrham [ST 73 75] to 75 m in the mid-Cotswolds.

In the south-west, the Dyrham Sand Formation (formerly Pennard Sand Formation) of the Sherborne-Shaftesbury area of Dorset, is up to 72 m thick, and comprises fine-grained sands and silts as in the Cotswolds type area. Occasional concretions are present in the Chard and Ilminster area. On the Dorset coast the upper two members of the Dyrham Formation are the Thorncombe and Down Cliff sands, which are underlain by clays. The Down Cliff Sand, 26 to 28 m of muddy, very fine-grained sands interbedded with sandy mudstone, is typical Dyrham Formation and probably of little significance as an aquifer. The succeeding Thorncombe Sand, also about 26 to 28 m, comprises cleaner fine-grained sand with concretionary calcareous cementation; it thins inland.

6.3.2.4 *Marlstone Rock Formation*

This formation is recognised from Market Weighton to south of the Mendips. Although the East Midlands Shelf and Cotswolds are described separately below, they were part of a single depositional basin, and the deposits are lithologically similar. The formation is only mapped separately from the immediately overlying Junction Bed north of Hawkesbury [ST 76 87] in Avon. It comprises a maximum of 9 m of ferruginous, sandy limestones.

Across the East Midlands Shelf, the Marlstone Rock comprises a calcareous ironstone, present throughout most of the region but absent for a few kilometres between Burton and Welbourne in the Lincoln area. It is overstepped by Cretaceous rocks at Market Weighton. Typically it is 3 m thick, but is substantially thicker in the Banbury area (up to 7.5 m) and in the Tilton-on-the-Hill (Leicestershire) to Grantham (Lincolnshire) area (up to 9 m). Generally it is a ferruginous, bioclastic often somewhat sandy limestone with ooliths where fresh; these weather to limonite and are seldom obvious in hand specimens. The formation is often conglomeratic at the base, where it rests on the Dyrham Formation or, north of Grantham where the Dyrham Formation dies out, on Charmouth Mudstone. In north-east Leicestershire the lower part is typically more sandy and less ferruginous, forming a calcareous sandstone, called the ‘Sandrock’. This is overlain by the typical ferruginous marlstone with its basal conglomerate; thus sedimentologically, this sandrock is part of the Dyrham Formation, although it is mapped as, and hydrogeologically forms part of, the Marlstone Rock Formation.

Pervasive oxidation and the development of limonitic joint infillings cause the Marlstone Rock to weather in a similar manner to the Northampton Sand (see Section 6.3.2.6), although it is usually less dramatic. It was worked extensively for ironstone in the area from Hellidon, south of Daventry to Banbury, with a quarry at Edge Hill still working. In the Tilton-Grantham area, it was worked until 1961; old workings have now generally been restored to farmland. It is overlain by the Whitby Mudstone Formation which restricts groundwater recharge down dip of the outcrop. It is affected by cambering and landslipping in some areas.

The Marlstone rock is present throughout the Cotswolds area, though it is apparently absent south of Bath in the neighbourhood of the Mendips. It is locally absent elsewhere, for example on the west side of the Vale of Bourton in the immediate neighbourhood of the Vale of Moreton Axis. It is allegedly up to 6 m thick but 1 to 3 m is more usual. Typically a ferruginous, rather sandy limestone, the upper part is often particularly ferruginous with altered ooliths. This more ferruginous facies is locally absent, for example in the Alderton Hill outlier, north of Winchcombe, Gloucestershire, where it is a grey calcareous sandstone. Generally it is less ferruginous than on the East Midlands Shelf. Locally the Marlstone Rock aquifer may include the ‘Subnodosus Sandstone’ in the underlying Dyrham Formation and the overlying ‘Junction Bed’ or ‘Cephalopod Limestone’ facies at the base of the succeeding Whitby Mudstone Formation.

The outcrop typically lies in the lower part of the Cotswold scarp slope sandwiched between the thick mudstone-dominated Whitby Mudstone Formation above and Dyrham Formation below. Consequently it is prone to landslipping and is often ‘lost’ at outcrop because of this; locally it forms broad spurs between landslipped areas, but is greatly affected by cambering and is therefore very heavily jointed. It is often heavily weathered and decalcifed at outcrop, but is more massive where unweathered at depth. Locally it forms a feeble spring-line.

Around Dursley [ST 75 97] the rocks dip eastward, but are slightly flexed and faulted locally and departures from

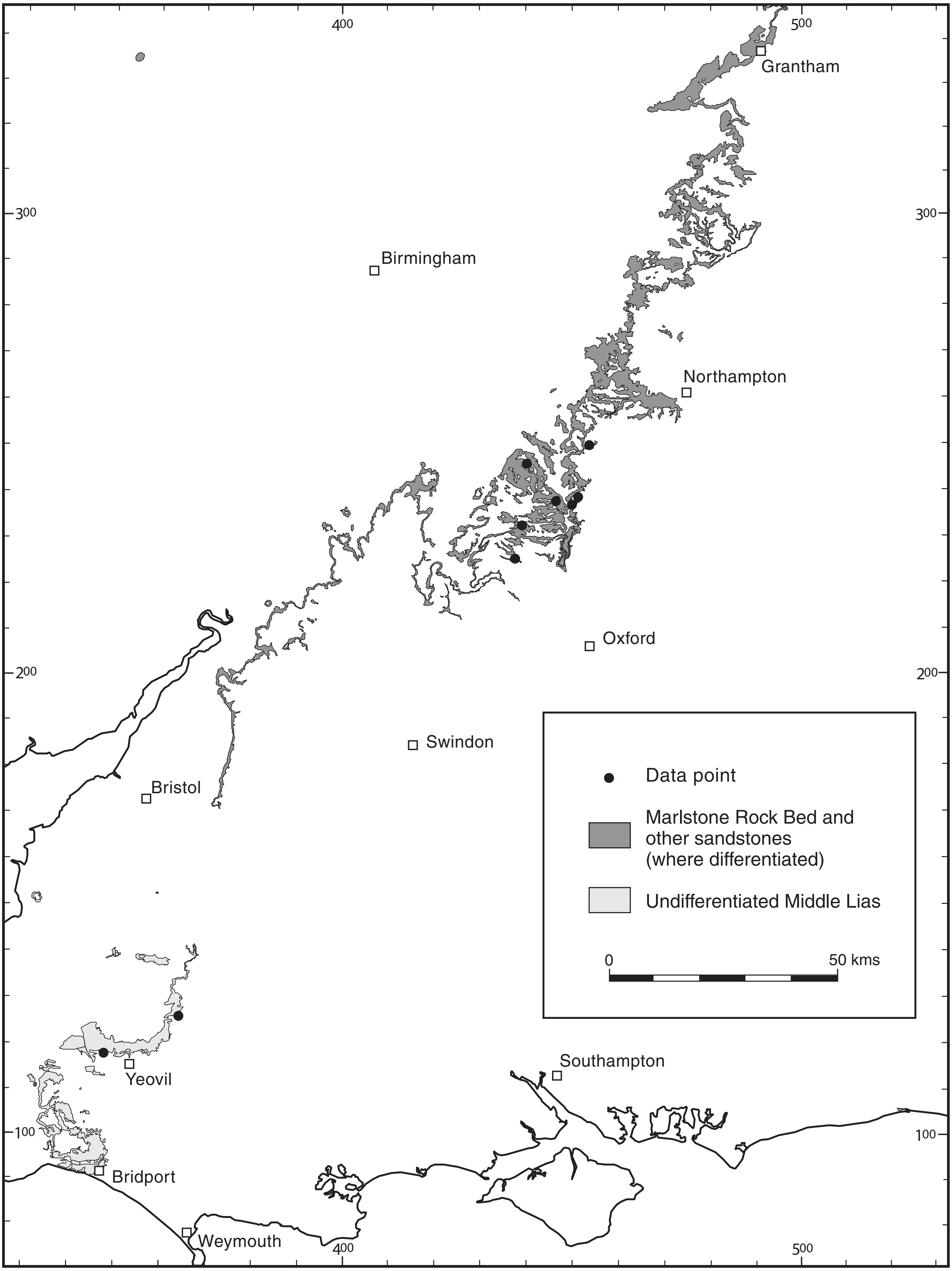

Figure 6.6 Outcrop of, and distribution of sites with pumping test data in, the Middle Lias (Dyrham Formation and Marlstone Rock Formation) of central and southern England.

regional dip, together with faulting, have been partly responsible for the meandering nature of the valleys which are still being developed by headward-growing tributaries of the Severn (Richardson, 1950).

The Marlstone Rock Formation in the Wessex Basin area is only 0.3 m thick on the Yeovil high. In south Somerset it is too thin to be mapped separately from the immediately overlying limestones known as the Junction Bed.

6.3.2.5 *Junction Bed*

The Junction Bed is best developed south of the Mendips and this area was described in Allen et al. (1997). Further north in the neighbourhood of the Mendips High it comprises up to 1.5 m of fine-grained ironstone and often conglomeratic limestone and marl. It rests non-sequentially on the Dyrham Formation or locally on the lower beds of the 'Lower Lias'. It is overlain by the Cotteswold Sands (now called the Bridport Sand Formation), from which it cannot be separated over most of the area, and is logically treated as part of this aquifer. It thins northwards to 0.2 m at Kelston, west-north-west of Bath.

North of Bath, where the sequence is more complete, the Marlstone Rock is present and the Junction Bed, as a separate recognisable aquifer, is effectively absent, although it is probably thinly represented as far north as Sodbury.

6.3.2.6 *Inferior Oolite Group*

The Inferior Oolite Group includes the Northampton Sand Formation, Grantham Formation, and Lincolnshire Limestone in the East Midlands Shelf area. In other areas, the group is simply subdivided into Upper, Middle and Lower Inferior Oolite. The group has largely been covered in Allen at al. (1997). O'Shea (1976, 1979) described the hydrogeology of the Inferior Oolite aquifer of the Upper Parrett basin in some detail.

Northampton Sand Formation

The Northampton Sand Formation is the basal unit of the Inferior Oolite Group throughout most of the East Midlands Shelf (Figure 6.7), lying unconformably on the Whitby Mudstone Formation. To the south-west, around Hook Norton in Oxfordshire, it passes into the Leckhampton Member (formerly Scissum Beds) of the Cotswolds. Northwards it dies out around Winterton, a few kilometres south of the Humber towards the Market Weighton High. Its area of maximum development is between Towcester and Grantham, with up to 20 m present near Northampton; but a more typical thickness is 5 to 8 m. Locally thicknesses vary due to channelling at the base of the overlying Grantham Formation. Typically the Northampton Sand consists of ferruginous sandstone, containing a variable proportion of ooliths, and is often calcareous or siderite-cemented. At and near outcrop it is generally pervasively weathered, oxidising to a soft rust brown coloured sandstone with brown-black limonite veins infilling joints and the development of formless segregations (known as boxstone weathering).

Grantham Formation (formerly Lower Estuarine Beds)

The Grantham Formation is present from just north of the Humber Estuary to Banbury. It is absent in the Lincoln area, north of Kettering, and locally further south. In the north, it comprises up to 8 m of sands with beds of carbonaceous clay, and may yield small quantities of water. Further south it also contains silts and clays with occasional calcareous sandstones.

In the Stroxton Valley, north-east of Well Head [SK 91 31] there is an area where the ironstone is largely absent. Here, the Grantham Formation occupies a broad channel or 'washout' in the underlying strata (Hollingworth and Taylor, 1951). Further south the aquifer is dissected by the Hollow Wood glacial channel (at SP 92 95 south of Harringworth). Elsewhere the ironstone is absent along some of the valley bulge structures.

Inferior Oolite limestone

The Inferior Oolite of the Midlands Shelf as far south as Kettering is called the Lincolnshire Limestone; its aquifer properties were described in Allen et al. (1997).

From Kettering south-westwards to the River Cherwell the limestones of the Inferior Oolite Group are replaced by the Northampton Sand Formation. Between here [SP 50 30] and the River Windrush [SP 30 10], the formation thickens, but is only 2.1 m thick at Fawler [SP 37 17]. The limited outcrop of limestones and sands generally provide water to wells and many small springs where they are underlain by impermeable strata. The water may be ferruginous.

West of the River Windrush the Inferior Oolite becomes a major aquifer again and was covered in Allen et al. (1997).

6.3.2.7 *Great Oolite Group*

The Great Oolite Group aquifers include the Fuller's Earth Rock Member, the Rutland Formation, the Great Oolite Limestone (and equivalents), and the Cornbrash Formation. Figure 6.8 shows the outcrop of the Great Oolite Group limestones in central and southern England. The majority of sites shown on the map refer to the major aquifers covered in Allen et al. (1997). In the Wessex Basin area, the Great Oolite Group is predominantly argillaceous at outcrop. The only potential aquifers in this area are the Forest Marble Formation and Fuller's Earth Rock.

Fuller's Earth Rock Member

The Fuller's Earth Rock Member is a thin (typically 4–6 m) unit of rubbly, shelly limestones which divides the Fuller's Earth Formation (predominantly clay) into lower and upper parts. It extends from the southern Cotswolds across the Mendips Axis, dying out south of Yeovil. North-east of Chippenham [ST 91 73] it passes into the lower part of the Great Oolite Group aquifer as the Upper Fuller's Earth. It is most important south of Bath where it thickens and forms modest outcrops at the foot of the Cotswold scarp; farther north the outcrop tends to disappear beneath landslips.

Rutland Formation (formerly Upper Estuarine Series)

The Rutland Formation is present possibly from north of the Humber to Brackley where it dies out. It is generally a non-aquifer but is sandy near the Humber, and in South Yorkshire it comprises well developed sands, up to 14 m thick, with overlying, northwards-thinning mudstones. The formation may extend as far north as Sancton [SE 89 39]. In north Lincolnshire the Rutland Formation consists of up to 20 m of pale sands (Thorncroft Sands) overlain by clays, silts and sands with impersistent coaly beds; limestones are present near Spital.

In south Lincolnshire it is 8 to 10 m thick consisting of 2 to 3 m of clays overlain by a rhythmic sequence of

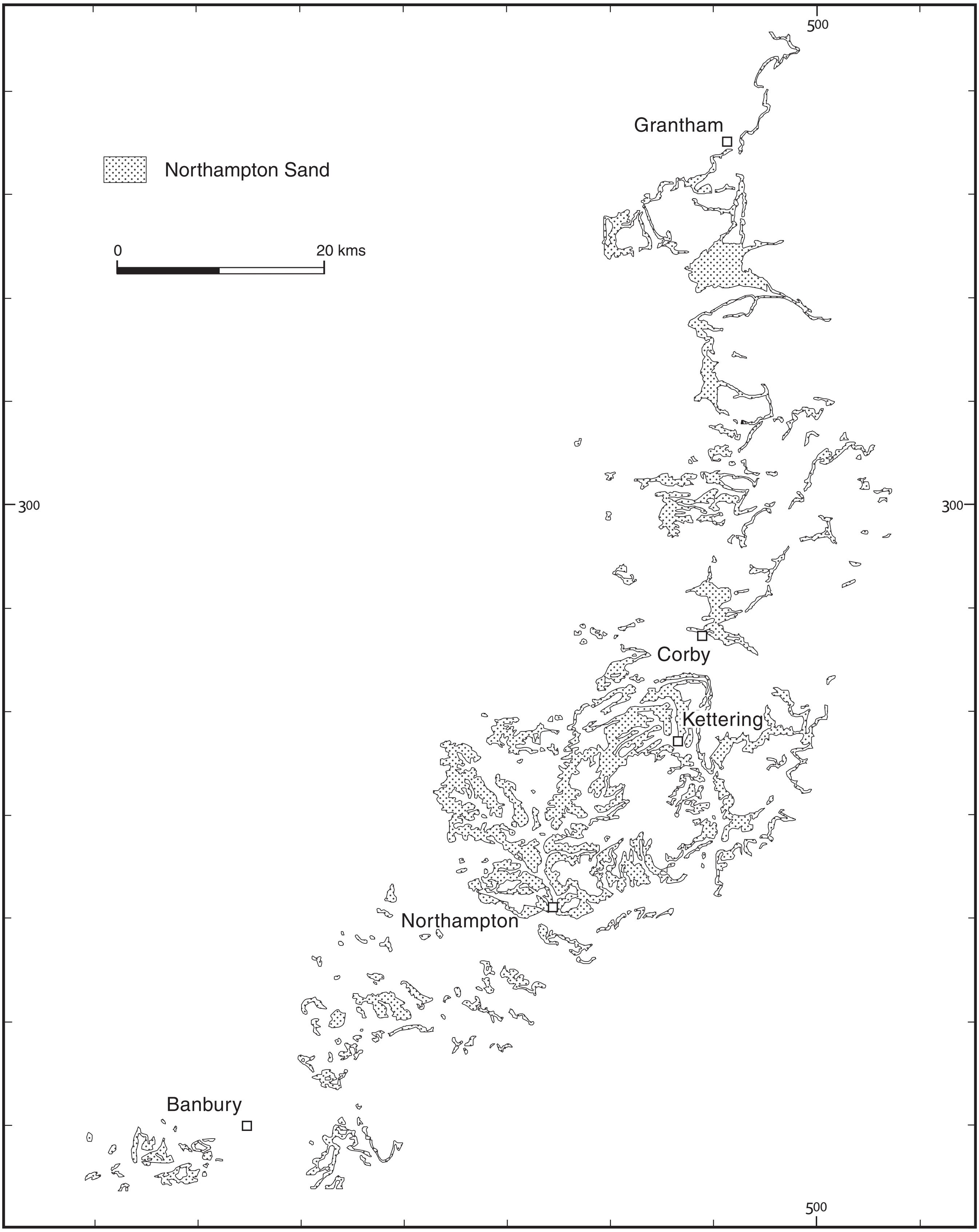

Figure 6.7 Outcrop of the Northampton Sand Formation.

limestones and clays. Further south-west it thickens to 20 m of silts, clays, mudstones with some sands at the base and limestones towards the middle and top.

North-east of the Cherwell the Chipping Norton Limestone is replaced by sands forming the lower part of the Rutland Formation.

Great Oolite Limestone and equivalents

The Snitterby Limestone, equivalent to the highest part of the Blisworth Limestone in the Midlands, is recognised from Brigg southwards. It is a thin, sandy limestone with a few shelly layers.

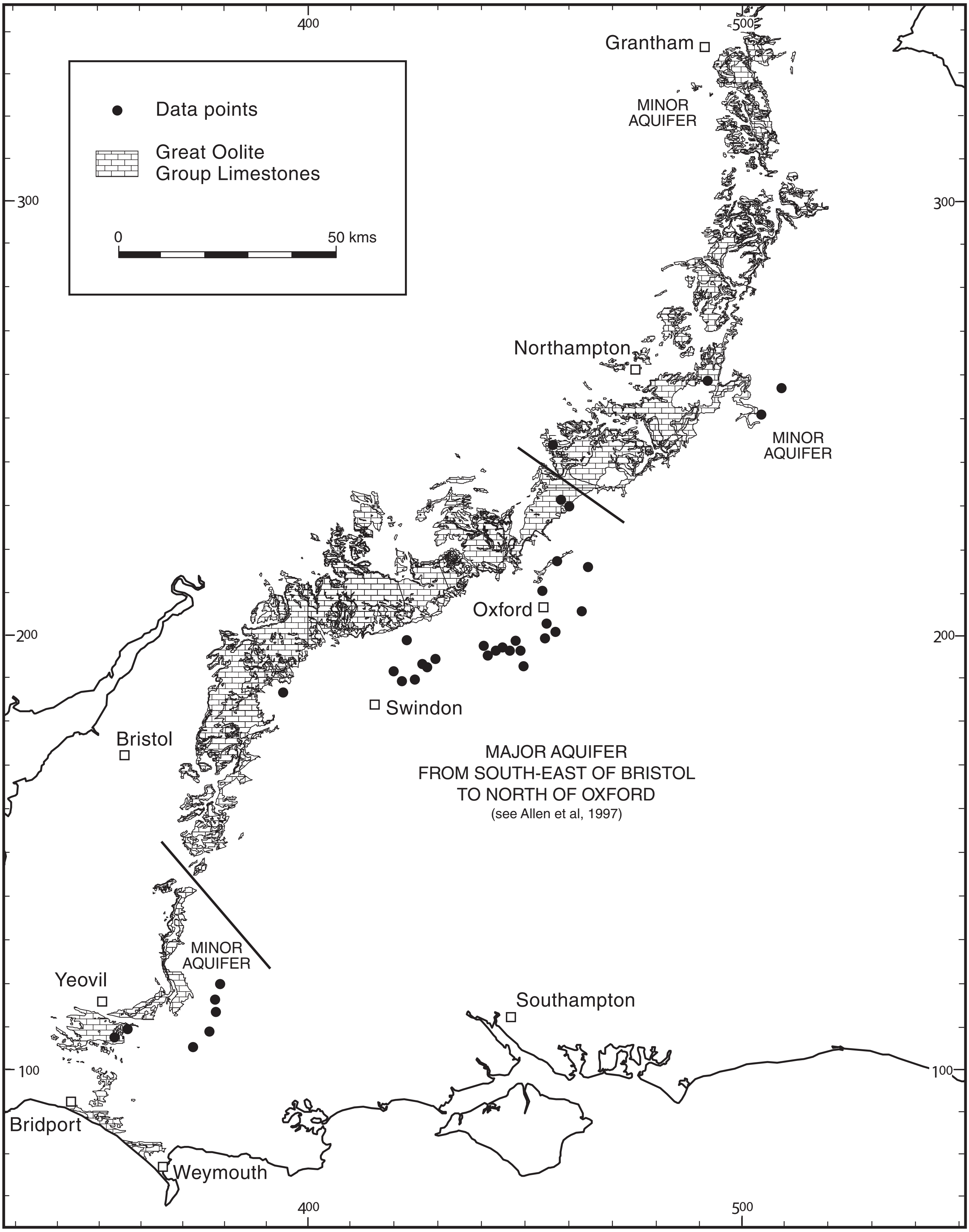

Figure 6.8 Outcrop of, and distribution of sites with pumping test data in, the Great Oolite Group limestones of central and southern England.

The Blisworth Limestone (equivalent to the Great Oolite Limestone) of the Midlands was covered in Allen et al. (1997). Between the Windrush and the Cherwell, the Great Oolite Limestone maintains its thickness, but the proportion of clays and shales increases to the north-east. As it occurs at high elevations, it tends to be dry, and hence is little used as an aquifer.

The Great Oolite Limestone of the Cotswolds was covered in Allen et al. (1997).

In the Wessex Basin, the Forest Marble is about 25 m thick on the coast and about 40 to 45 m thick inland in the Sherborne-Shaftesbury area. It is essentially a unit of mudstone with lenticles and laminae of sandy or shelly limestone, and larger bodies of flaggy, shell fragmental, oolitic limestone and calcareous sandstones. In contrast to the Cotswold type area, the major limestones tend to occur in the middle, and to a lesser extent upper part of the formation.

Downdip, beneath Hampshire, Sussex, Surrey and Kent, limestones are present. Sellwood et al. (1989) studied the effects of late cementation processes on the Great Oolite carbonate reservoir of southern England. The rocks comprise limestones which provide a significant hydrocarbon reservoir facies. They concluded that although the carbonates suffered early diagenesis under marine conditions, later diagenetic cements were volumetrically more important in reducing the porosity on a regional scale.

Cornbrash Formation

The Cornbrash forms the uppermost unit of the Great Oolite Group, generally separated from the main part of the Great Oolite aquifer by clays. It typically comprises 2 to 3 m of fissured limestones and marls and is present from just north of the Humber southwards to the Dorset coast (Figure 6.9), crossing all three main depositional areas. It reappears again in the Cleveland Basin (see Section 6.2.2.6).

The Cornbrash is present throughout most of the East Midlands Shelf region, but is absent north of the Humber, apart from minor remnants (e.g. at North Ferriby). This is apparently due to overlap by Kellaways Formation onto the Market Weighton High, rather than to Cretaceous overstep. The formation is typically 2 to 3 m thick, but may reach 6 m. It comprises hard, bioclastic limestone with minor beds of marl and is often quite shelly; it is poorly bedded, and rubbly to unevenly flaggy due to intense burrowing. The Cornbrash overlies Forest Marble clays in the south-west and the Blisworth Clay farther north, and is overlain by the Kellaways Clay. Although thin it may produce extensive dip slope outcrops particularly at the fen edge from Peterborough to just south of Lincoln.

In the Cotswolds the Cornbrash comprises 3 to 5 m of rather rubbly, fine-grained limestone with thin beds of clay or marl. It typically forms extensive outcrops at the foot of the Cotswold dip slope.

In the Wessex Basin the Cornbrash comprises fine-grained shell fragment and oolitic limestone, marly limestone and slightly sandy limestone. It is typically rubbly at the base, and more sandy and better bedded in the upper part. It reaches a maximum thickness of about 10 m on the coast near Weymouth and inland as far as the Shaftesbury-Sherborne area (where up to 12 m is claimed), then thins to 3 m towards the 'Mendip Axis', largely by a progressive loss of Upper Cornbrash (as is typical for the rest of the country). It occurs sandwiched between the Forest Marble and Kellaways clays and is probably only a significant aquifer in the south, where it is thickest.

6.3.2.8 *Kellaways Sand Member*

The Kellaways Sand Member and underlying 2.5 to 20 m thick Kellaways Clay Member (within the Kellaways Formation) occur at the base of the Oxford Clay, a thick sequence of clays and shales. It is present from Dorset northwards to North Newbald, where it is cut out by the Cretaceous overstep over the Market Weighton High, but reappears in the Cleveland Basin as the Redcliff Rock Member of the Osgodby Formation (see Section 6.2.2.7).

In the East Midlands Shelf area the Kellaways Sand Member typically comprises 2 to 4 m, perhaps up to 7.5 m, of fine-grained sands and fine-grained sandy/silty mudstones; the coarser beds sometimes being patchily carbonate-cemented into concretionary layers. In the Cotswolds the Kellaways Sand Member comprises 3 to 4 m of fine-grained sands and calcareous sandstones. The sandstones ('Kellaways Rock') are best developed to the south-west of Fairford [SP 15 01] in Gloucestershire and again tend to exhibit concretionary, nodular cementation. The Kellaways Sand Member in the Wessex Basin comprises 0.5 to 4 m of sandy limestone.

6.3.2.9 *Corallian Group*

The Corallian Group south of the Market Weighton High can be divided into two distinct areas. From Humberside to a few kilometres east of Oxford it forms part of the thick argillaceous sequence that extends in age from the Oxfordian to the Kimmeridgian. Within these clays there are only two small areas where limestones are developed: in Humberside (the Brantingham Formation), and in Cambridgeshire and Bedfordshire (the West Walton Formation). From Wheatley south-westwards, it comprises a varied sequence of sandstones, clays and bioclastic limestones with local developments of coral, underlain by the Oxford Clay and overlain by the Kimmeridge Clay. The Osmington Oolite of Dorset, was described as a major aquifer in Allen et al. (1997); the other less important aquifers in this area are described here. The following description of the geology divides the permeable parts of the Corallian Group into three main geographical areas: Humberside to east Oxford, the south Midlands, and the Wessex Basin. Figure 6.10 indicates the outcrop, and sites from which there are pumping test data, from Cambridgeshire to the south coast.

Humberside to east Oxford

BRANTINGHAM FORMATION

The Brantingham Formation occurs beneath Quaternary cover on both sides of the Humber. It comprises a sequence of sandstones, siltstones and limestones which reach 15 m in thickness in the Alandale borehole [TA 0007 2584], where they are also most arenaceous. The formation cannot be identified south of Worlaby. Sandstones are limited to the lower part of the formation in the area where it is of maximum thickness between Brough and Hessle. The upper part there, and most of the formation elsewhere, is predominantly siltstone.

WEST WALTON FORMATION

Two parts of the West Walton Formation are minor aquifers, the Upware Limestone and the Elsworth Rock.

The Upware Limestone outcrops between Upware and Barway [TL 55 72] and comprises up to 11 m of cross-bedded oolitic limestone and sandy coral limestones.

The Elsworth Rock Group is present from Sandy [TL 180 495] to west of St. Ives [TL 29 72]. It comprises

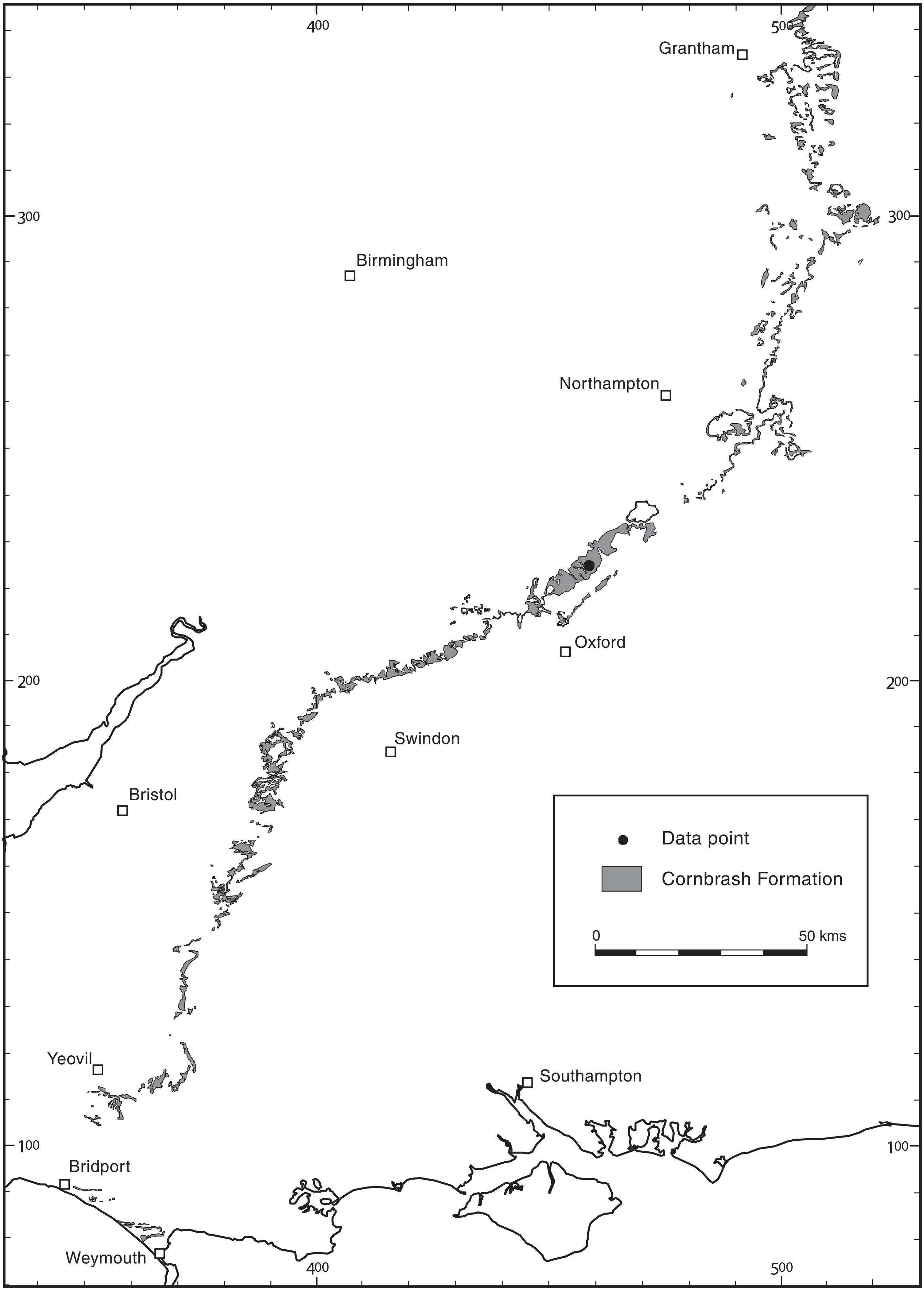

Figure 6.9 Outcrop of, and distribution of sites with pumping test data in, the Cornbrash Formation of central and southern England.

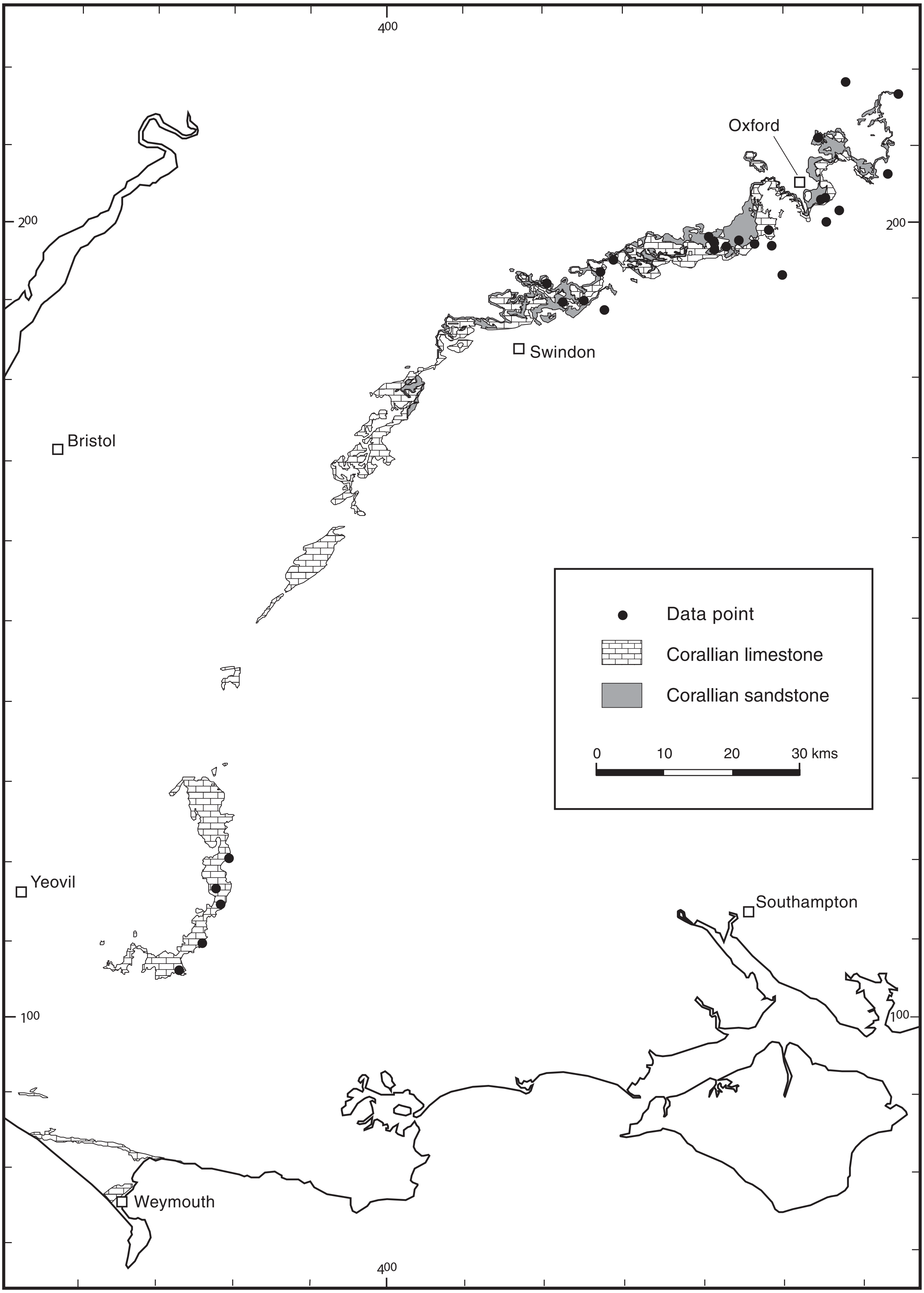

Figure 6.10 Outcrop of, and distribution of sites with pumping test data in, the Corallian of central and southern England.

up to 5 m of limestones, which vary from alternating thin argillaceous limestones and clays at Sandy to two beds of oolitic limestone separated by clays or occasionally sandy beds at Elsworth.

South Midlands

In the south Midlands, the Corallian crops out in a west-south-west to east-north-east trending belt, dipping south-south-east between approximately Calne in Wiltshire and the Oxford area. It crosses the Vale of Moreton Axis, forming a range of hilly ground that separates the Vale of the White Horse (to the north of the Chiltern scarp), from the Thames valley. It comprises a complex association of sands/calcareous sandstones and shallow-marine limestones (coralliferous in part) together with silts and mudstones. The total thickness of the Corallian may be 35 m through Calne, Swindon and Oxford, though around Oxford the basal parts tend to be very silty (Temple Cowley Member) and the aquifer part of the group is probably 20 m or less. It thins to the north-east and south-west by lateral passage into mudstones of the West Walton Formation and is overlain with a slight non-sequence by the Ampthill Clay. It probably does not extend far down dip of outcrop. Thus the aquifer is completely enclosed by aquitards.

The basal part of the aquifer tends to comprise sands with concretionary calcareous sandstones e.g. Beckley Sand, Lower Calcareous Grit. This is succeeded by shell fragmental (not oolitic) limestones which include coral debris (e.g. Wheatley Limestone, 'Coral Rag'), but no coral reefs as such. In the area between Swindon and Faringdon, the Coral Rag is overlain in turn by the Red Down Clay and the Red Down Sand. The limestones tend to be rather soft, are not well cemented and are very porous. The aquifer is affected by major faults and periclinal structures east of Oxford (Wheatley Fault Zone). These faults may have had a component of Jurassic movement which controlled the deposition of the Corallian and affected groundwater flow.

Wessex Basin

The Corallian is well exposed on the Dorset coast, and outcrops in North Dorset (Mere Basin), but is absent because of Cretaceous overstep between these areas, and over the Mendips at the north of the Wessex Basin. It is up to 60 m thick or more on the coast. It is a rather complex, but essentially cyclical, succession comprising mudstones passing up into calcareous sandstone and limestones, the latter including oolites and, locally, corals. Thus there are three main units of limestone/sandstone separated by argillaceous strata:

[mudstone]
Sandsfoot Grit
[mudstone]
Bencliff Grit + Osmington Oolite + Coral Rag + Clavellata Formation
[mudstone]
Nothe Grit + Preston Grit

NOTHE GRIT FORMATION (FORMERLY LOWER CALCAREOUS GRIT)

The Nothe Grit Formation comprises 9 m of fine- to medium-grained sand with concretionary cementation and some more argillaceous layers. These units become more argillaceous inland passing into the Hazelbury Bryan Formation, which comprises up to about 50 m of sandy mudstone with some water-bearing sandy limestone units.

REDCLIFF FORMATION/STOUR FORMATION (APPROXIMATING TO THE FORMER BERKSHIRE OOLITES)

These formations are dominantly mudstones, about 15 m thick on the coast where they include 2 m of sandy limestone (Preston Grit Member) at the base, and the 5 m thick Bencliff Grit Member at the top. They are thicker inland, including up to 11 m of limestone, the Cucklington Oolite Member.

OSMINGTON [OOLITE] FORMATION

This is about 20 m thick on the coast and 10 m in north Dorset, it comprises mainly oolitic limestone, including uniform limestones but is often nodular or marly particularly at the base. It is a major aquifer in this area and its porosity and hydraulic conductivity were discussed in Allen et al. (1997).

CORAL RAG FORMATION

The Coral Rag Formation occurs locally in north Dorset, and comprises up to 2 or 3 m of rubbly, fossiliferous and coralline limestone.

TRIGONIA CLAVELLATA FORMATION

The Trigonia Clavellata Formation is a rather complex unit reaching about 5 m thickness on the coast, but increasing to 10 m in the north. It comprises mainly limestones and marls.

SANDSFOOT FORMATION

At the base of the Sandsfoot Formation is the Sandsfoot Clay Member (mudstones and sandy mudstones). It is about 6 m on the coast, probably rather thinner in north Dorset. This is succeeded by the Sandsfoot Grit Member (approximating to the former Upper Calcareous Grit), which is about 6 or 7 m thick on the coast, and about the same in north Dorset, although locally increasing to perhaps 9 or 12 m at the expense of the underlying clay. This member comprises medium- to coarse-grained, more or less ferruginous and calcareous, sandstones with lenses of oolitic ironstone.

RINGSTEAD FORMATION

The Ringstead Formation includes mainly mudstones equivalent to the Ampthill Clay of central England. This is succeeded by Kimmeridge Clay.

6.3.2.10 *Kimmeridge Clay*

The Kimmeridge Clay is predominantly argillaceous, however in the South Humberside area it contains the Elsham Sandstone which forms a minor aquifer and in Dorset the clay provides local supplies. The sands at the top of the Kimmeridge Clay in the south Midlands (Thame and Wheatley Sands) are described with the overlying beds in Section 6.3.2.12.

Elsham Sandstone Formation

The Elsham Sandstone is a medium to coarse-grained sandstone lens occurring within the upper part of the Ancholme Clay Group, in the Elsham area south of the Humber estuary. It was originally thought to be an outlier of Spilsby Sandstone, but has now been dated as Lower Kimmeridgian based on faunal evidence (Gaunt et al., 1992). The sandstone is up to 9 m thick and is present from Bonby [TA 008 148], where it is truncated northwards beneath the sub-Carstone unconformity, southwards almost to Barnetby le Wold [TA 052 105], where it wedges out (see also Section 5.5.1).

Kimmeridge Clay of Dorset

The Kimmeridge Clay comprises mudstones that are at various levels calcareous, bituminous, silty or sandy.

6.3.2.11 *Portland and Purbeck groups*

These groups outcrop between Whitchurch and Swindon as isolated outliers, then reappear further south in the Vale of Pewsey (Portland Group only), Vale of Wardour, south Dorset and in the Wealden Basin (where only the Purbeck Group outcrops at the surface) (see Figure 6.11). The Portland Limestone Formation at the top of the Portland Group in south Dorset was discussed in Allen et al. (1997), the rest of the deposits are described here.

The outcrop of the Upper Kimmeridge Clay sands, Portland and Purbeck groups and Whitchurch Sand Formation is shown in Figure 6.11.

Upper Jurassic and Lower Cretaceous outliers of the south Midlands

These outliers include outcrops of the Thame and Wheatley Sands, Portland Group, Purbeck Group and the Whitchurch Sand Formation [Shotover Sand]. The rocks cross the Vale of Moreton Axis, occurring on both the East Midlands Shelf and in the Worcester Basin.

The Thame and Wheatley sands occur at the top of the Kimmeridge Clay, but are included here as they are in hydraulic continuity with the overlying Portland beds. The Thame Sand occurs in the Thame–Long Crendon area, it is up to 15 m thick and comprises sands and silts. The Wheatley Sand around Wheatley consists of clean, fine-grained sands.

The Portland Group outcrops on the hills of Swindon Old Town and in the area between east Oxford, Thame and Aylesbury; the latter forming the most extensive (and northerly) outcrops in Britain. The deposits are up to 13 m thick, but are more typically 10 m where complete, and generally less because of overstep. They comprise a lower unit of 3 to 5 m of greenish, glauconitic sand (loosely speaking Portland Sand or Glauconitic Beds) which may be calcareously cemented into a nodular or more continuous sandstone; there is often a pebbly layer at the base (Upper Lydite Bed). These sands are overlain by limestones (Portland Stone). These include sandy limestones, often with large bivalves and giant ammonites. They are often hard and well-cemented but include beds of uncemented sand. This 'Portland Stone' has been used for building but is different from its namesake on the Isle of Portland.

The Purbeck Group is less extensive than the Portland Group but is preserved as small, insignificant outliers around Swindon and more extensive outcrops between Thame (Oxon) and Aylesbury (Bucks); its most northerly occurrence is at Stewkely near Leighton Buzzard. It is up to 6.6 m thick, but is generally thinner. It comprises white, fine-grained limestones with marl beds, the latter occurring particularly at the base. The limestones contain stromatolites, shrinkage cracks and other indicators of lagoonal sedimentation; they are often intensely hard and re-cemented, and (probably) well-jointed.

The Whitchurch [Shotover] Sand is basal Cretaceous, Wealden Group (Horton et al. 1995) in age, but in some accounts has been wrongly regarded as latest Jurassic. It is described here as this is where its hydrogeological affinity lies. It occurs as scattered outliers between Shotover Hill [SP 567 063] and Whitchurch [SP 796 210], consisting of up to 20 m or more of very permeable, ferruginous, but generally uncemented sands.

Portland Sand Formation of southern England

The Portland Sand Formation is restricted at outcrop to the coastal areas of Portland and Purbeck; it is cut out farther north by the Cretaceous overstep, although small 'outliers' occur north-east of Shaftesbury in the Vale of Wardour, and in the Vale of Pewsey. The formation is present at depth beneath the Weald where the succession is thicker, though more argillaceous.

Using the traditional classification, the Portland Sand of the Dorset coast is about 20 to 40 m thick, increasing towards Purbeck. The thickest succession tends to be argillaceous in the lower part, with the 'sands' (the Black Sandstones and West Wear Sandstones), best developed in the upper part, and possibly 7 to 15 m thick. These are grey or brown dolomitised calcarenites, comprising up to 50% quartz sand, but containing no true sandstones.

Purbeck Group of southern England

This group comprises the Lulworth Formation (Jurassic in age) and overlying Durlston Formation (Cretaceous in age). The Lulworth Formation is about 60 m thick at Purbeck, thinning to the west. The lower part of the formation is dominated by thinly bedded fine-grained limestones, with some marly layers, and stromatolites and evaporites indicating lagoonal deposition; this is overlain by a generally more argillaceous upper part. The Durlston Formation mainly comprises limestones and shales.

In the Vale of Wardour 24 m of Lulworth Formation are preserved and the overlying Durlston Formation is sandy. However the Purbeck Beds contain little water and that present is of poor quality.

The Purbeck Group of the Weald consists of a maximum thickness of 170 m of shales with horizons of limestone, sandstone and gypsum.

6.3.3 Hydrogeology

This section covers the hydrogeology and aquifer properties of the formations described in Section 6.3.2, where there is sufficient relevant information. However, due to the disparate nature of many of the aquifers, there are frequently very limited data, and in some cases, formations are not discussed further.

6.3.3.1 *Blue Lias Formation*

As described in Section 6.3.2.1, the Blue Lias Formation across much of England is similar, although the marginal facies of Wales and the Mendips are quite distinct. A few small springs ooze from the outcrop of the formation, and at the top of the underlying less permeable Penarth Group; yields are low and decrease in summer. They form precarious supplies when tapped in wells, where yields vary but rarely exceed 40 m^3/d.

Groundwater quality is generally hard and often poor, possibly saline or containing hydrogen sulphide from decomposing pyrites in the shales.

The aquifer properties data collected was attributed to the Lower Lias, undifferentiated, and this is how it has been analysed and discussed. However, it is likely that the pumping test data is predominantly from the Blue Lias.

There are 52 porosity values for the Lower Lias ranging from 1.1 to 27.5% with an arithmetic mean of 9.4% (Table 6.2 and Figure 6.12). The highest values occur in the Worcester Basin. There are 18 hydraulic conductivity values ranging from less than the detection limit to 0.28 m/d, with a geometric mean of 1.5×10^{-4} m/d (Figure

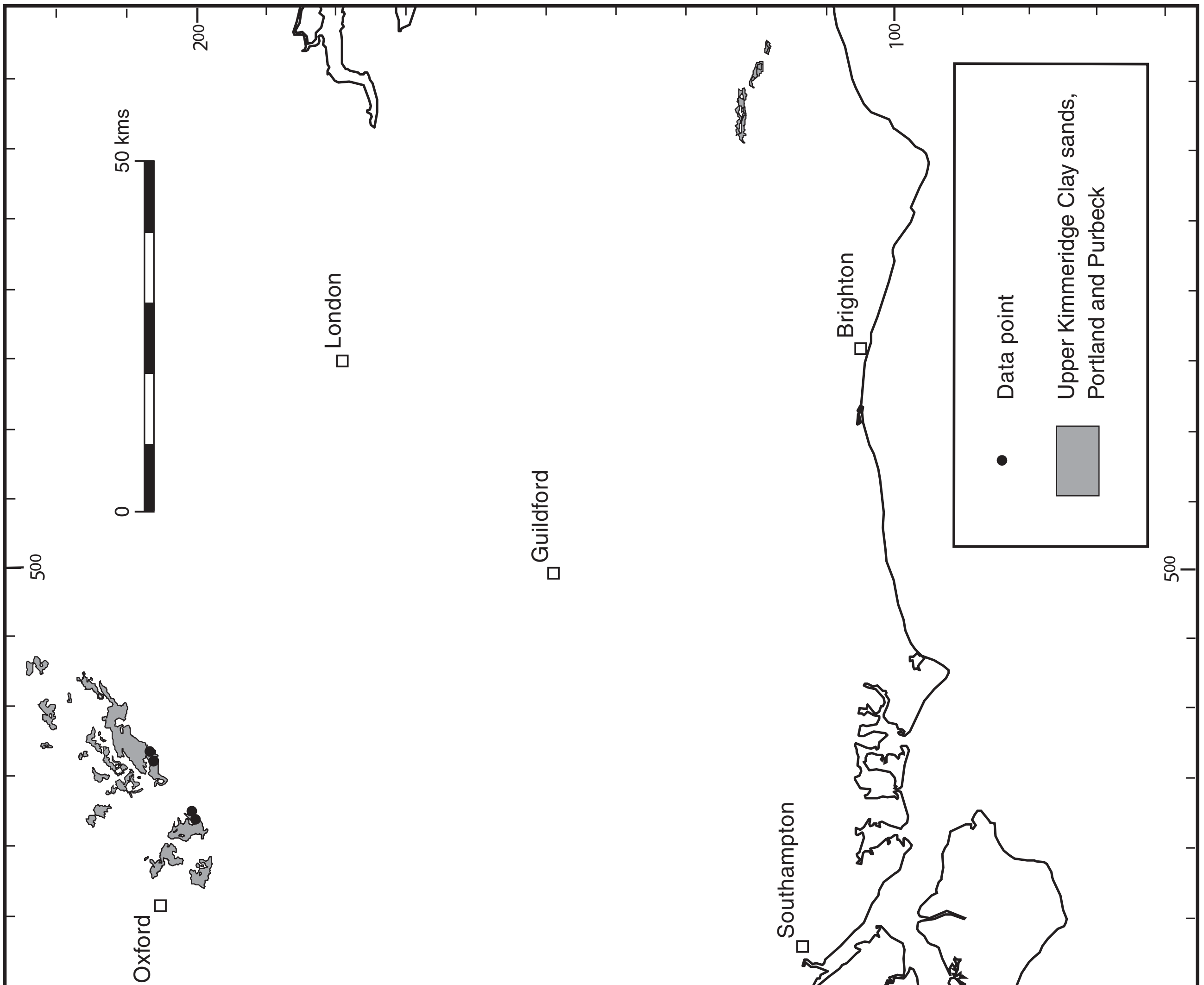

Figure 6.11 Outcrop of, and distribution of sites with pumping test data in, the upper Kimmeridge Clay sands, Portland and Purbeck groups and Whitchurch Sand Formation.

6.13). In general higher porosities correspond with higher hydraulic conductivities (Figure 6.14), but the correlation is poor. Both porosity and hydraulic conductivity values were surprisingly lower from outcrop samples than borehole samples (Table 6.2).

The outcrop of, and distribution of sites with pumping test results in, the Lower Lias are shown in Figure 6.5. The results are summarised in Table 6.3. The storage coefficients range from 1.5 × 10^{-1} to 1.5 × 10^{-4}. There are nineteen transmissivity values from sixteen locations; they vary from 2 to 426 m^2/d and have a geometric mean of 20 m^2/d (Figure 6.15). There are twenty six specific capacity values from twenty three locations, they vary from 0.13 to 920 $m^3/d/m$. They approximate to a log-normal distribution and have a geometric mean of 15 $m^3/d/m$ (Figure 6.16). There is a positive correlation between transmissivity and specific capacity (Figure 6.17: y = 2.75 x–26.6, r^2 = 0.77), with both the highest values from the northern part of the East Midlands Shelf.

East Midlands Shelf

In the East Midlands Shelf area the permeable parts of the Blue Lias Formation are the thin limestone bands and a calcareous sandy belt present towards the top. Yields are generally less than 40 m^3/d, for drawdowns of up to 60 m, and some wells are dry. The highest recorded yield from the

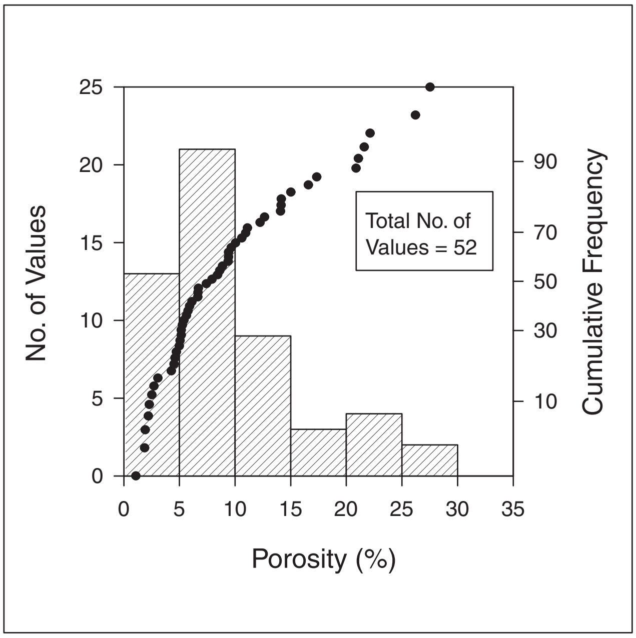

Figure 6.12 Distribution of porosity values for Lower Lias samples.

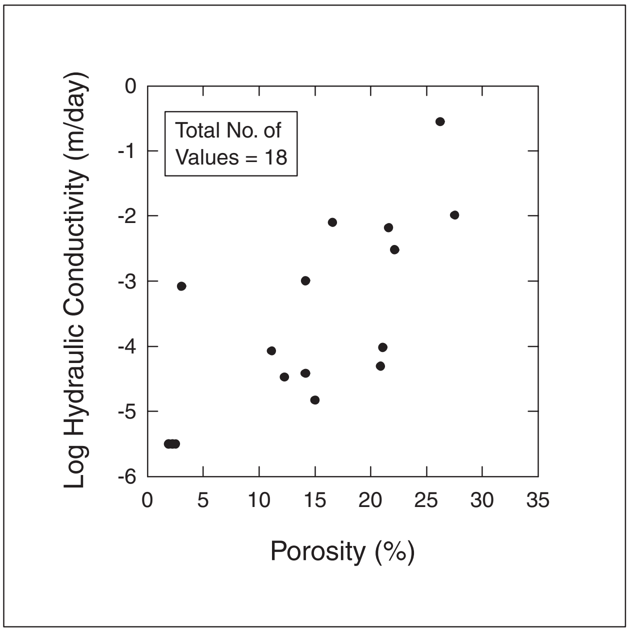

Figure 6.14 Plot of hydraulic conductivity against porosity for Lower Lias samples.

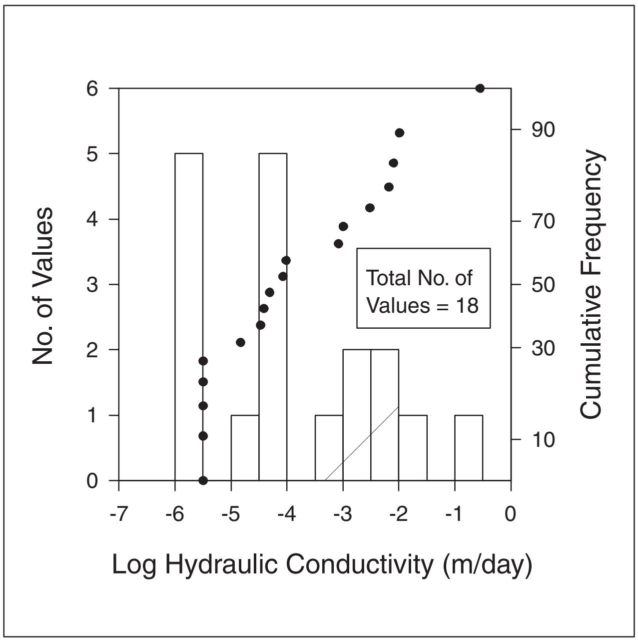

Figure 6.13 Distribution of hydraulic conductivity values for Lower Lias samples.

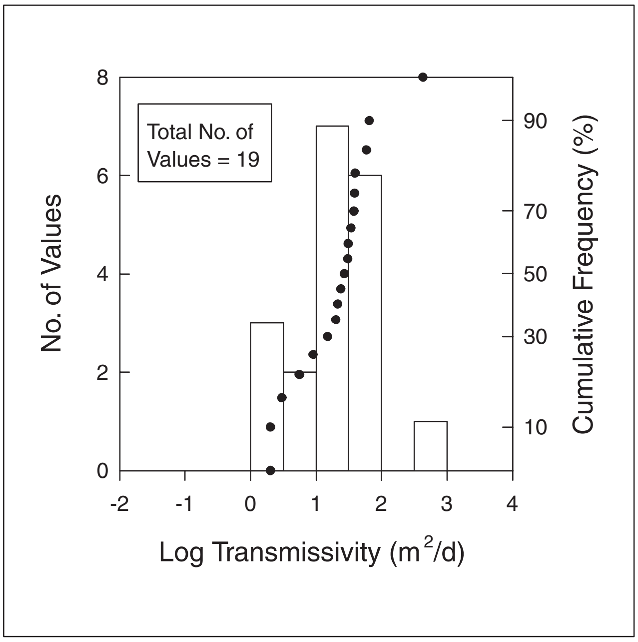

Figure 6.15 Distribution of transmissivity values from pumping tests in the Lower Lias.

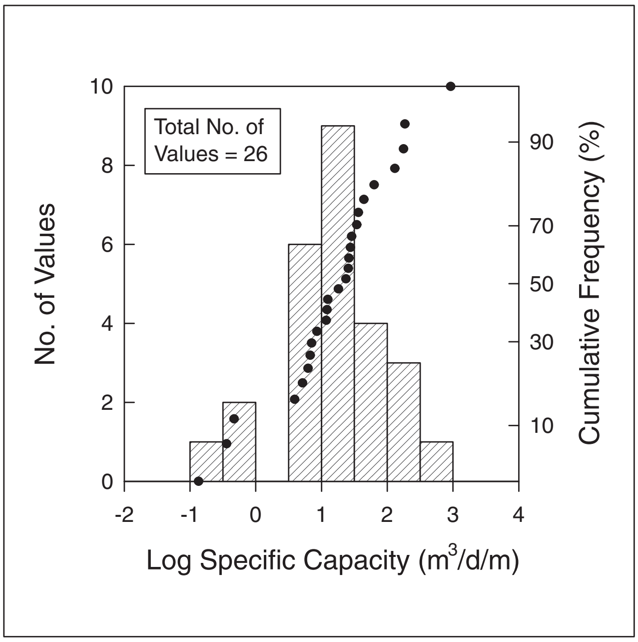

Figure 6.16 Distribution of specific capacity values for the Lower Lias.

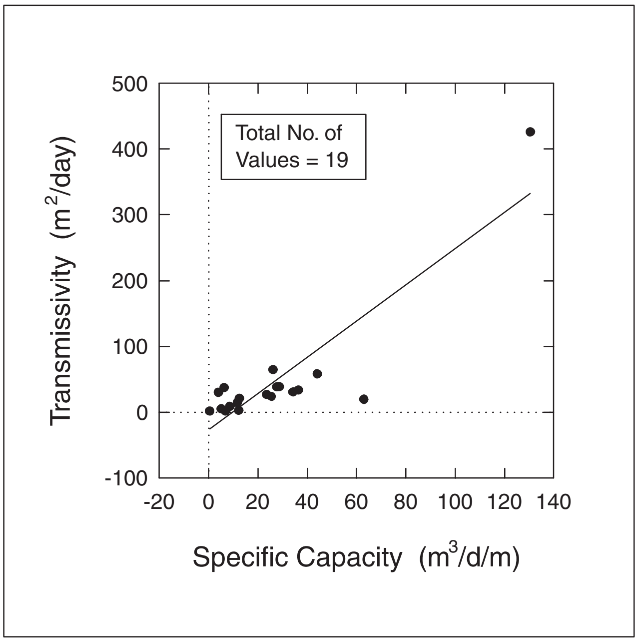

Figure 6.17 Plot of transmissivity against specific capacity for the Lower Lias.

Blue Lias is 110 m^3/d at Starveall, Stretton-on-Fosse [SP 2130 3923], but a 240 mm diameter, 55 m deep bore penetrating both the Lower Lias and the Mercia Mudstone at Bevington Hall, near Evesham [SP 0529 5235] yielded 220 m^3/d for a drawdown of 44.8 m.

Mineral springs occur at several locations, examples being near Bishopton in Warwickshire [SP 185 564] and at Shearsby Spa in Leicestershire [SP 6215 9015]. However, at Lutterworth, Leicestershire [SP 537 850] the groundwater is soft with a temporary hardness of 84 mg/l (as $CaCO_3$) and no permanent hardness.

There are seven porosity values from samples from depths ranging between 51 and 218 m from a borehole at Thorpe [SP 8857 9648], they range from 1.1% to 9.4% with a mean of 5.7%.

There are eight sites where pumping tests have been carried out, the transmissivity values range from 6 m^2/d at The Oaklands, Edstaston, near Wem [SJ 5112 3269] to 426 m^2/d at Manor Farm, Wolston, Warwickshire [SP 4395 7351], the geometric mean is 24 m^2/d. The 14 values for specific capacity range from 0.13 m^3/d/m to 920 m^3/d/m, with a geometric mean of 15 m^3/d/m.

Worcester Basin

Twelve samples were available for the Lower Lias from depths of between 430 and 435 m at a borehole at Harwell, Oxfordshire [SU 4680 8644]. Porosities ranged from 11.1 to 27.5%, and hydraulic conductivities from 1.5×10^{-5} to 3×10^{-1} m/d.

Pumping tests have been carried out on four boreholes. Two tests on each of three boreholes through Lower Lias, probably penetrating Blue Lias, at Slimbridge, Gloucestershire [SO 72 04] produced transmissivity values varying from 27 to 65 m^2/d and storage coefficients generally of about 1.5×10^{-4}, but in one case of 5×10^{-3}. The test on Blue Lias at Hillview Nurseries, Twyning, Gloucestershire [SO 8905 3654] gave a transmissivity value of 2 m^2/d. Both these locations are in the northern part of the basin. Specific capacity values at the same locations varied from 6.2 to 36.4 m^3/d/m.

Wales

In the Blue Lias, small calcareous and ferruginous springs occur at the base of the Porthkerry Formation, around Lavernock [ST 18 68], where alternating limestones and shales overlie the Lavernock Shales. There are no boreholes into the Blue Lias in the Cardiff area, but further west, 100 mm diameter boreholes generally yield up to 40 m^3/d and a 305 mm, 122 m deep borehole at Rhoose Cement Works [ST 0640 6615] yielded 1220 m^3/d of good quality water.

Mendips

In the Mendips, the Lower Lias is represented by massive limestones known as the Downside Stone. Where this directly overlies the Carboniferous Limestone, there is hydraulic continuity between the Lower Lias and Carboniferous Limestone and water passes down into the underlying rocks. Where the Penarth Group shales or other impermeable rocks intervene a perched water table may occur within the Downside Stone, or the shales may simply confine water in the underlying Carboniferous Limestone. For example, a shaft and adits at Shepton Mallet [ST 628 431] sunk through the Lower Lias (Downside Stone and thin shaly bands) and Penarth Group into the Carboniferous Limestone, failed to obtain any water from the Lias, although water from the Carboniferous Limestone rose above the top of the limestone, suggesting that the shales in the Lias and Penarth Group confine water in the underlying Carboniferous Limestone. However even where the Penarth Group is present, some degree of hydraulic continuity generally exists between the Lias and the Carboniferous and hence appreciable supplies are not generally found in the Downside Stone. At Darshill in the Sheppey Valley, to the west of Shepton Mallet, strong springs issue from the base of the Downside Stone at a rate of 1135 m^3/d, implying that some of the water is derived from the Carboniferous Limestone, although two bores drilled into the limestone nearby were dry. Another borehole drilled within 60 m of the springs, penetrating Lower Lias, Penarth Group, Blue Anchor Formation, Dolomitic Conglomerate and Carboniferous

Limestone, yielded 220 m^3/d during a ten hour test. In the Sheppey valley, to the east of Shepton Mallet, a borehole at ST 626 436 through 21 m of Lias and thin Penarth Group, into the Carboniferous Limestone to a depth of 43 m, had an artesian flow of 112 m^3/d. Test pumping at 560 m^3/d for seven days, depressed the water level to 25 m, but on cessation of pumping recovery took only 37 minutes. The yield of a Lower Lias limestone spring 200 m up the valley was diminished approximately in proportion to the amount pumped and a second 60 m deep borehole 100 m away was dry (Green and Welch, 1965).

Wessex Basin

Water occurs in the jointed limestones, with springs issuing from the junction of these limestones and the White Lias with the underlying Black Shales of the Penarth Group, particularly on the scarp slopes in the central part of the basin along the Somerset/Devon border. Shallow boreholes rarely yield more than 20 m^3/d. The water is hard and sometimes saline.

Along the North Somerset coast the Lower Lias is often covered by alluvial deposits. A borehole near Alstone House, West Huntspill [ST 3171 4678] penetrated 3.8 m of drift above 35.8 m of Charmouth Mudstone and Blue Lias and yielded 275 m^3/d. Another 153 m deep borehole at Bason Bridge, Somerset [ST 3444 4548] also through drift, Charmouth Mudstone and Blue Lias obtained 210 m^3/d of brackish water.

Six analyses from outcrop samples at Hinckley Point [ST 2150 4620] gave porosities in the range 1.9 to 3.1% and hydraulic conductivities ranged from below the minimum measurable to 8.3×10^{-4} m/d. Twelve samples from outcrops along the Dorset coast around Lyme Regis had porosities ranging from 5.1 to 14.1% and 15 from two boreholes at Charmouth [SY 365 930] at depths of between 46 and 84 m had porosities varying from 2.7 to 17.3%.

There are four values of transmissivity available for this area, varying from 2 to 58 m^2/d. The three values for storage coefficient are between 0.14 and 0.15. The five specific capacity values range from 0.5 to 176 $m^3/d/m$.

6.3.3.2 *Frodingham Ironstone*

Both the Frodingham Ironstone and the thinner Pecten Ironstone of north Lincolnshire (slightly higher in the sequence), are well-jointed and produce small springs and a few domestic supplies.

A 60 m deep borehole into the Frodingham Ironstone at Twigmoor Grange [SE 9205 0504] had a transmissivity of 0.16 m^2/d and a specific capacity of 1.3 $m^3/d/m$.

6.3.3.3 *Dyrham Formation*

The Dyrham Formation extends from Grantham in the north to the Dorset coast in the south. It is considered to be most important as an aquifer in the south.

In the East Midlands and Cotswolds, the best developed spring line is at the base of the Dyrham Formation at the contact with the underlying Charmouth Mudstone, particularly in the Malmsbury area of the Cotswolds (Cave, 1977). In the Wessex Basin many springs issue from the Dyrham Formation, and several were used for public supply in the Symondsbury, Morecombelake, Chideock area (e.g. SY 4128 9389 and SY 4302 9366). Some springs form river sources. Around Chipping Norton the springs thrown out at the junction with the underlying Lower Lias have low discharges (Horton et al., 1987).

In the Wessex Basin, where it is sandy, the formation is tapped by many shallow wells. The aquifer is improved by being in hydraulic continuity with the overlying Junction Bed, increasing the recharge area. In the East Midlands, at Merriscourt Farm, south of Churchill [SP 29 21] where the overlying Marlstone Rock Formation is thin or absent, two boreholes failed to obtain water from the siltstones. Around Tadmarton, wells tapping the Marlstone Rock Formation and underlying Dyrham Formation have poor yields and large seasonal water level variations, for example, 5.3 m at Castle Farm, Bloxham [SP 4194 3767].

Laboratory physical properties data (Table 6.2) for the Middle Lias was not analysed separately for the Dyrham Formation and Marlstone Rock. The distribution of porosity values does not follow a log normal distribution (Figure 6.18); the mode is between 25 and 30%. Hydraulic conductivities generally approximate to a log normal distribution (Figure 6.19) and this is reflected in a rather poor correlation between increasing hydraulic conductivity and higher porosity values (Figure 6.20). Data are only available for the East Midlands and Wessex Basin, and only the latter has pumping test data (Table 6.3).

A sample from the Middle Lias of the East Midlands at a depth of 7 m from a borehole at Thorpe [SP 8857 9648] had a porosity of 25%. In the Wessex Basin, six samples from a borehole into the Middle Lias at Winterbourne Kingston [SY 8470 9790] at depths of between 1115 and 1140 m had porosities varying from 8.4 to 29.5% and hydraulic conductivities from 9×10^{-6} to 6.9×10^{-4} m/d. Three samples from outcrops on the Dorset coast south of Lower Eype [SY 44 91] had porosities ranging from 12.2 to 15.6%.

In the Cotswolds, a 45 m deep borehole at Frogmarsh Mill [SO 8409 0176] starting in the Whitby Mudstone Formation and probably continuing into the Dyrham Formation had a transmissivity value of 75 m^2/d from siltstones. There are two transmissivity values for the Middle Lias of the Wessex Basin: 3 and 50 m^2/d. The four specific capacity values range from 13.3 to 201 $m^3/d/m$.

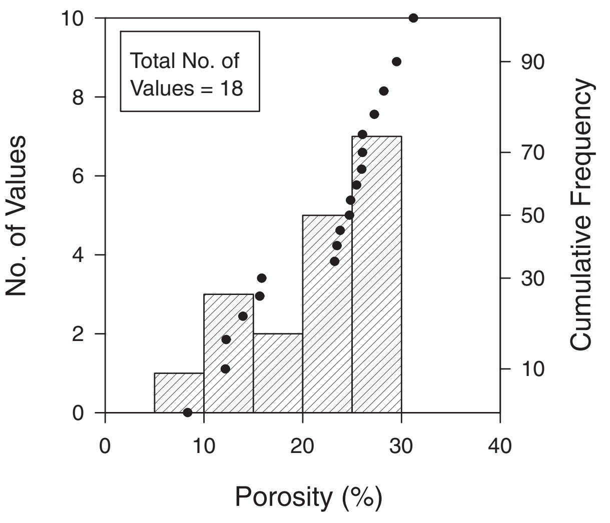

Figure 6.18 Distribution of porosity values for Dyrham Formation samples.

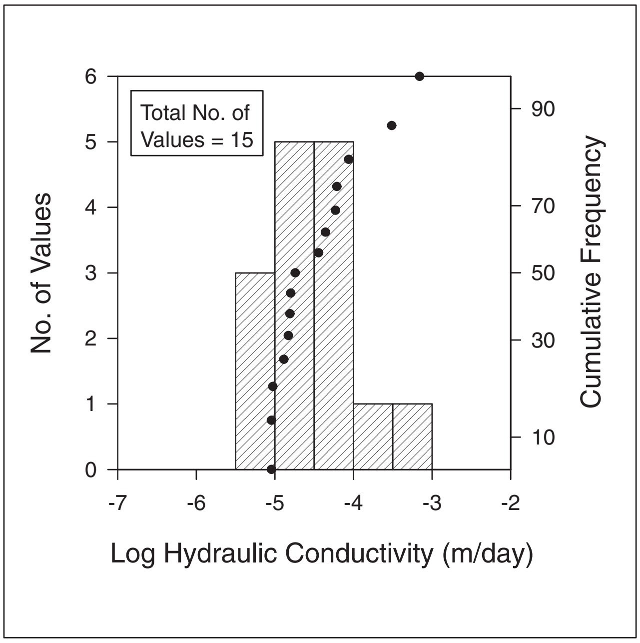

Figure 6.19 Distribution of hydraulic conductivity values for Dyrham Formation samples.

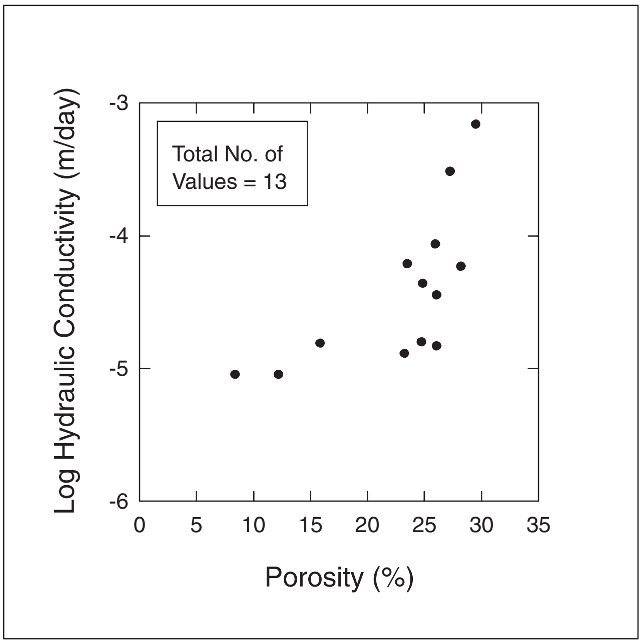

Figure 6.20 Plot of hydraulic conductivity against porosity for Dyrham Formation samples.

Yields from shallow boreholes (less than 25 m deep) in the Wessex Basin, range from 35 to 220 m^3/d; yields over 100 m^3/d are not always maintained.

6.3.3.4 *Marlstone Rock Formation*

The Marlstone Rock is the most important minor aquifer in the Middle Lias with groundwater contained in, and transported through, a regionally developed fissure system. Both weathered and unweathered Marlstone Rock are very fine-grained (almost crystalline where unweathered) indicating a low matrix permeability and high porosity. However it is fractured into blocks and weathered where water has penetrated. Water flow is therefore predominantly along fissures with possibly small or non-existent matrix flow. Due to a high degree of fracturing, Solomon (1996) predicted that the transmissivity and storage coefficient were likely to be higher at outcrop, and lower at depth where less fracturing and weathering had occurred.

Most information has been found for the Marlstone Rock in the East Midlands Shelf area. Here, springs with flows of up to 85 m^3/d are common from the base of the formation, but some have yielded up to 430 m^3/d, such as those north of Scalford [SK 77 25], which historically supplied Melton Mowbray and at Ebrington [SP 1886 4006] which supplied Shipston-on-Stour. Borehole yields are rarely over 40 m^3/d due to the restricted outcrop of the formation.

The Marlstone Rock is an important building stone around Edge Hill, Duns Tew and Great Tew, where it is very hard and fractured. In this area the underlying Middle Lias is a sequence of sandy siltstones and clays, connected by fracturing. A number of springs and surprising number of boreholes in the confined aquifer obtain water from the Marlstone Rock and sandy siltstones below.

Solomon (1996) carried out a detailed study of the southern part of the aquifer within the Thames Region of the Environment Agency. Around Edgehill [SP 37 47] the Marlstone forms a scarp face on the north-west edge of its outcrop and dips south-east at 0.3Þ, with perhaps slight folding between Chipping Norton and Banbury, and south of Brackley. The formation is not persistent and wedges out downdip. Groundwater generally flows south-east under confined conditions, coinciding with the north-west to south-east dip, but there is a groundwater mound in the centre of the study area, due west of Chipping Norton. This indicates an area of either increased recharge or lower hydraulic continuity or storage. The groundwater gradient is low, approximately 1 in 250. East of the River Cherwell groundwater movement is largely controlled by a westward piezometric gradient towards the river. West of the Cherwell water is recharged along the north-west edge of the escarpment and by the headwaters of the River Glyme, and also from the Middle Jurassic limestones along major faults.

There are a large number of springs marked on the topographic maps, but Solomon (1996) did not observe any flowing in summer. He also calculated that the recharge to the aquifer is more than two orders of magnitude greater than the abstraction from it. Therefore he postulated that the discharge to rivers is small compared with the amount of recharge the aquifer receives, with much of the water escaping as leakage into the Dyrham Formation siltstones below. This is supported by the fact that the best developed spring line is at the base of the Dyrham Formation. The Marlstone Rock is therefore assumed to be in hydraulic continuity with the underlying siltstones.

The quality of water from the Marlstone Rock is generally good but hard and often ferruginous. There is a mineral spring at Newfoundland Well, near Ilmington [SP 2050 4378] (Williams and Whittaker, 1974). Solomon (1996) noted that, as expected, iron and manganese levels were higher in waters from wells than from springs, with reducing waters at depth. Nitrate ion concentrations are higher than the maximum admisssible concentration (of 50 mg/l NO^{-}_{3}) at some sources (both springs and wells) due to the fractured nature of the aquifer and rapid recharge.

Core data

Nine outcrop samples from the Marlstone Rock at Alkerton Quarry [SP 389 428] had porosity values varying from

23.2% to 31.2%; the hydraulic conductivities ranged from 9×10^{-5} to 9×10^{-4} m/d.

Solomon (1996) stated that the porosity varied from 10.3% (least weathered) to 41% (most weathered) and intrinsic permeability from 0 (least weathered) to 16.15 m/d (most weathered). He estimated from this intrinsic permeability data that the maximum transmissivity arising from flow through the matrix would therefore be 160 m^2/d where the Marlstone Rock is thickest, but generally only 30 m^2/d. However the presence of fractures would increase the transmissivity beyond this range.

Solomon also used the elastic storage equation to estimate specific storage and storage coefficient. Taking the compressibility of confined limestone to be 10^{-10} m^2/N, and using porosity values from his laboratory work, he calculated the specific storage to be in the range 1.41×10^{-6} m^{-1} to 2.71×10^{-6} m^{-1}. Therefore where the Marlstone Rock is 10 m thick, the confined aquifer storage coefficient could not exceed 2.7×10^{-5}. If he had used the compressibility of jointed rock, the maximum storage coefficient would be 10^{-4}.

Pumping test results

Solomon (1996) used Logan's equation (transmissivity = 1.22 × yield/drawdown) to estimate transmissivity values which varied from 10 m^2/d at Chipping Norton [SP 2885 2831] to 1220 m^2/d at Eydon Hall [SP 5385 4976]. Four out of his six values were in the range estimated from intrinsic permeabilities (10, 10, 40, and 60 m^2/d). It is reasonable to conclude that in these cases, the wells tapped an aquifer where the permeability was only marginally enhanced by fracture flow. The other two values were an order of magnitude higher, Eydon Hall and Astrop Hill Farm (790 m^2/d, SP 5118 3818), suggesting a greater degree of fracturing. However it should be noted that this method is really only suitable for confined rather than leaky confined aquifers, and is therefore not strictly applicable.

There are seven values of specific capacity which range from 7 to 1000 m^3/d/m, with a geometric mean of 77 m^3/d/m (Table 6.3). Again the range would be consistent with a flow regime where fractures do not always play a dominant role.

Yield data

In the Chipping Norton district (Horton et al., 1987), a supply of 690 m^3/d was obtained from a well deepened by a borehole at Bloxham [SP 425 356], and a nearby borehole yielded 850 m^3/d for 0.6 m drawdown. Yields are less than 50 m^3/d in the north around Upper Astrop [SP 510 375], for drawdowns of between 3 and 13.7 m. At Upper Heyford [SP 4953 2603], pumping at 220 m^3/d produced 3.7 m drawdown. Abstraction takes place from wells at Church Enstone [SP 3802 2511] which yields 85 m^3/d for no appreciable drawdown, and around Glympton [SP 4256 2168] with a yield of 470 m^3/d for 1.2 m drawdown. Boreholes at Middle Barton [SP 4322 2641] and Westcott Barton [SP 4329 2624], both sited on the Great Oolite outcrop, obtained their supplies from the Marlstone Rock at depth; their yields were respectively 80 and 140 m^3/d for a drawdown of 0.5 m.

The dam of the Rutland Water reservoir [SK 94 07] is located 25 m above the Marlstone Rock, and during its construction and filling, seepages from the Marlstone were monitored (Horswill, 1978). Interestingly, the permeability of the fresh rock at depth was found to be two orders of magnitude higher than that of the weathered rock and residual soils present at the surface. Relief wells were installed downstream of the dam to control uplift pressures and monitor seepage flows. During impounding the artesian flows from the relief wells increased steadily to 14 000 m^3/d, until the reservoir was 1.5 m below top water level, when they then suddenly increased to 16 500 m^3/d. Submersible pumps increased the discharge to between 24 000 and 18 000 m^3/d which stopped the potentiometric pressure (which had reached 6 m of head) from rising further. The investigations into the increased seepage were focussed on known well positions and outcrops beneath the reservoir including valley bulge sites (Horswill, 1978).

Only seven specific capacity values were obtained from the initial data collection exercise; these ranged from 7 to 1000 m^3/d/m with a geometric mean of 77 m^3/d/m. Additional yield data and licensed abstraction quantities were compiled from the National Well Record Archive for grid squares SP 22, 23, 32, 33, 34, 41, 42, 43, 44, 45, 52, 53, 54, 55, 56, 57 and 65. Licensed abstraction data were also collected from Thames and Anglian regions of the Environment Agency. These data were collated into a single database. Plots of daily licensed quantity against grid reference did not show any regional variations (Figure 6.21); plots of other parameters similarly showed no regional variation. The maximum, minimum, mean and interquartile range for hourly yield, specific capacity, and daily licensed quantity are shown in Table 6.8. The distribution of daily licensed quantity and yield are shown in Figures 6.22 and 6.23. Both datasets have a log-normal distribution and, interestingly, yields are typically an order of magnitude greater than the licensed quantity, possibly indicating they may only be sustained for a few hours. The specific capacity values from the BGS records were significantly lower than those collected directly from the Environment Agency offices, reflecting a bias in the latter data towards higher yielding sources. This is a natural but inherent bias, reflecting the tendency to apply for abstraction licenses only for the more successful wells. The 39 values obtained from the BGS records range from 0.35 to 504 m^3/d/m, with a geometric mean of 14 m^3/d/m. These specific capacities were combined with those from the Environment Agency, and duplicates removed. The distribution of all the data is shown in Figure 6.24.

In the Cotswolds, springs issue from the junction of the Marlstone and Middle Lias Clays at Caswell [ST 7657

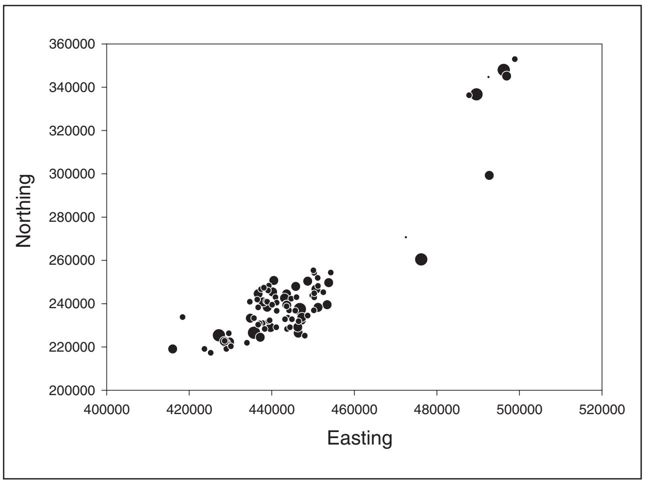

Figure 6.21 Areal distribution of daily licensed quantity values for the Marlstone Rock Formation.

Table 6.8 Yield data for the Marlstone Rock Formation of the south Midlands.

Licensed quantity (m^3/d)					
No. values		Interquartile range	Min.	Max.	Geometric mean
93		3.6–18.2	0.55	909	9.5
Yield (m^3/d)					
No. values		Interquartile range	Min.	Max.	Geometric mean
99		26–120	1.4	1090	55
Specific capacity (m^3/d/m)					
No. values	No. sites	Interquartile range	Min.	Max.	Geometric mean
39	38	5–50	0.35	504	14

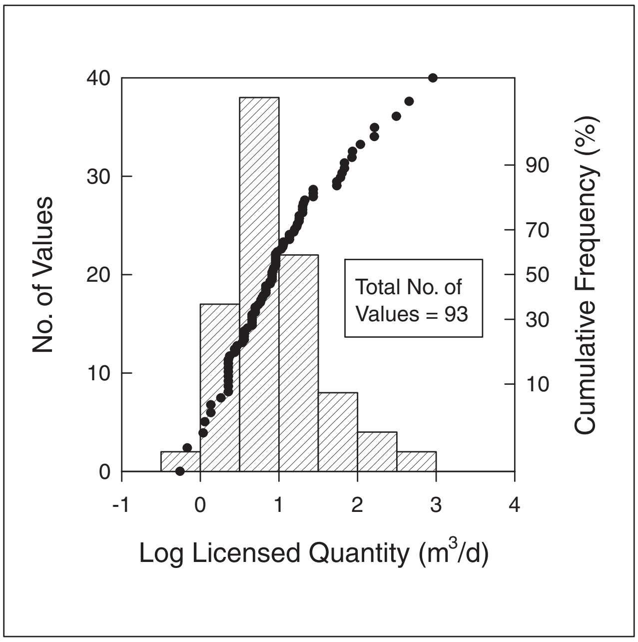

Figure 6.22 Distribution of daily licensed quantity values for the Marlstone Rock Formation.

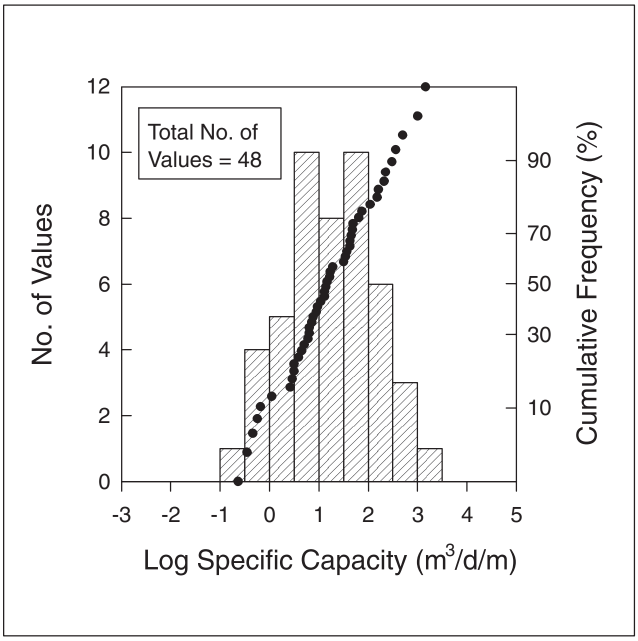

Figure 6.24 Distribution of specific capacity values for the Marlstone Rock Formation.

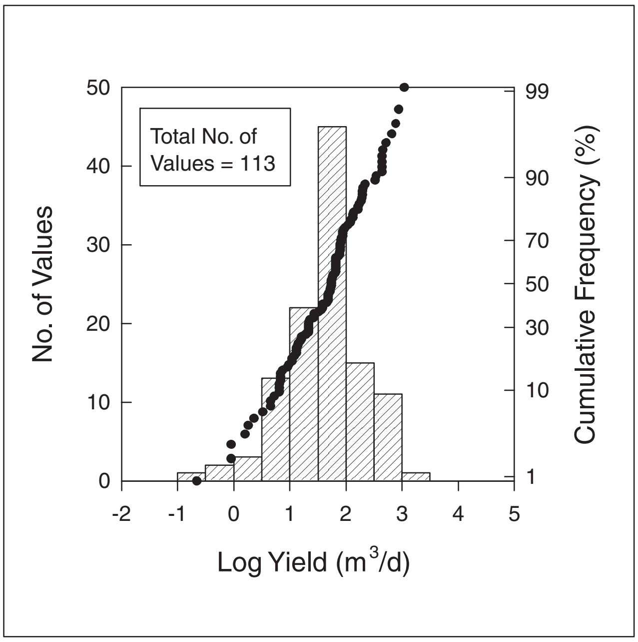

Figure 6.23 Distribution of yields for the Marlstone Rock Formation.

9739] and Millend [ST 7512 9643]. At Caswell the spring is collected through a system of pipes in a trench and is largely derived from Bridport Sand (formerly the Cotteswold Sands). Before it was intercepted it probably gave rise to a stream joined by water from the base of the Marlstone Rock below the pumping station. The spring takes six weeks to respond to rainfall. Richardson (1950) quoted a maximum yield from the pumping station of 1818 m^3/d in June 1932 and a minimum of 860 m^3/d in September 1945. At Millend the Marlstone is 6.1 m thick and has a narrow outcrop. Yields are relatively high, augmented by water flowing over the edge of the Upper Lias clay where it thins over the Marlstone due to denudation and faulting. Richardson (1950) stated that 654 m^3/d was used and another 182 m^3/d was available. At Dursley [ST 7672 9761] an 18.9 m deep well of 1.8 m diameter through Upper Lias into Marlstone, yielded 760 m^3/d and much more in wet weather (Richardson, 1950). The rest water level was 15 m below ground level and it was cased to 13.4 m.

At Fawler [SP 3687 1731] a good spring from the Marlstone Rock had flows varying from 130 m^3/d in December 1933 to 1400 m^3/d in October 1927 (Richardson et al., 1946).

6.3.3.5 *Northampton Sand Formation*

Groundwater flow in the Northampton Sand Formation is a combination of matrix and fracture flow. Where weathered, the formation is very porous, as the cement has been leached out (Offodile, 1972). As a result groundwater movement occurs by both intergranular and fracture flow, whereas in the lower unoxidised sandstones groundwater movement is predominantly via fracture flow. Therefore the sands form the more reliable aquifer at shallow depths (generally less than 10 m) beneath the ground surface or superficial deposits. Generally intergranular flow predominates except where fractures are well developed. The latter occur, for example, where blasting during mining has left fractures in the aquifer beneath worked areas, where boxstone weathering has occurred, or where the strata are upturned in valley bulge structures. Figure 6.25 illustrates how competent sandstones of the formation are dislocated by bulging of the underlying, incompetent Lias clays. Springs occur at the junction of the sands with the underlying Whitby Mudstone. Those at Shotwell Mill [SP 8170 8264], north of Rothwell were used for water supply, having a maximum yield of 1068 m^3/d in 1934. Since then their flow has ceased due to opencast working of the ironstone in the Rothwell area.

In the Stroxton valley, water in the Northampton Sand Formation moves south-east down dip as far as the line of the washout where impermeable Grantham Formation rests on Lias clay, forming a barrier to any further movement. The water thus breaks out on the valley side at Well Head [SK 9000 3062], where a heading has been driven west-south-west in the ironstone for a distance of 400 m. This provided up to 909 m^3/d and was the water supply for Grantham, until it became polluted.

Northampton Sand water is generally of good quality but hard.

Aquifer properties

The formation was most heavily utilised in northern Northamptonshire. A 1.9 m diameter shaft, which entered Northampton Sand at 11.9 m. at Corby Pumping Station [SP 8928 8929] used to supply the village with 455 m^3/d. At Burton Latimer Pumping Station [SP 8861 8055], a trial shaft bottoming Northampton Sand at 8.8 m gave a poor yield but a second 10.7 m deep shaft with five headings at a depth of 9.1 m yielded 455 m^3/d. At Clover Hill Pumping Station [SP 8692 7989], a shaft with two headings at the base of Northampton Sand yielded 220 m^3/d. Yields do not increase with depth, and smaller yields have been obtained from boreholes at depths of 30 m or more. For example, a well at Southwick Hall [TL 0199 9166], penetrating Northampton Sand at around 32 m yielded 85 m^3/d. A borehole at Deenethorpe [SP 9693 8939], entered Northampton Sand at 44.5 m and yielded 140 m^3/d during a six day test, although the yield was possibly augmented by formations above the sands. A number of wells and boreholes have proved unsuccessful. A boring at the Co-operative Dairy in the north of Kettering [SP 8677 8030], bottoming the Northampton Sand at 11 m and a 23.5 m deep well to the base of the Northampton Sand at Cinquefoil Lodge, Warkton [SP 9121 7945] both failed to obtain a supply. The formation no longer provides public or other major supplies in the Northamptonshire area.

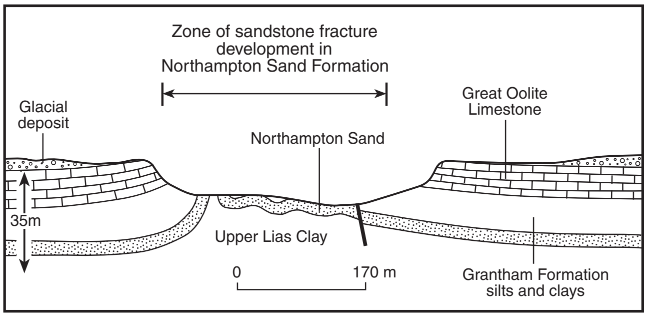

Figure 6.25 Fracture development in the Northampton Sands Formation due to valley bulge structures (from Blyth and de Freitas, 1984, after Hollingworth et al., 1944).

In Oxfordshire the Northampton Sands are generally unconfined, with wells penetrating them in the area immediately east of the River Cherwell having higher potential yields than those into the oolites higher up the succession. A well at Souldern [SP 525 314], tapping 7.3 m of Northampton Sands yielded 220 m^3/d for 0.3 m drawdown and at Somerton [SP 502 285], a yield of 280 m^3/d was obtained for no measurable drawdown from a 4.3 m saturated section. At Upper Heyford [SP 5194 2568], a yield of 360 m^3/d was obtained from a well, for 3.7 m drawdown from 6.2 m of Northampton Sands of which only the basal 4.9 m was saturated. At Upper Tadmarton [SP 3929 3779], pumping at less than 20 m^3/d incurred no drawdown from a 1 m saturated section at the base of a 1.5 m diameter shaft penetrating 8.8 m Northampton Sands.

In south Lincolnshire, boreholes into the Lincolnshire Limestone are frequently continued down into the Northampton Sand Formation. Where there is hydraulic continuity between the Northampton Sand Formation and the Lincolnshire Limestone this increases the overall transmissivity. Where the Northampton Sand is 6 m thick and fully saturated, it is likely to have a transmissivity of around 60 m^2/d; this is unlikely to be significant in the confined area, where the transmissivities of the Lincolnshire Limestone are above 1000 m^2/d, but at outcrop, where saturated thicknesses and hence transmissivities are lower, a contribution from the Northampton Sand Formation is more important.

Further south in northern Northamptonshire, boreholes into the Lincolnshire Limestone are similarly continued down into the Northampton Sand Formation. The largest supplies are obtained where the Lincolnshire Limestone has channelled down into the Northampton Sand, where the Grantham Formation is thin or absent or in quarry workings where the two formations are effectively one aquifer. At Desborough Pumping Station [SP 8459 8563], 12.4 m of Upper Lincolnshire Limestone and 6.9 m of Northampton Sand, beneath 9.1 m of Rutland Formation, yielded 409 m^3/d. At Little Oakley [SP 895 857] an 11 m deep well penetrating 3 m of Upper Lincolnshire Limestone over 5.2 m of Northampton Sands had a yield of 818 m^3/d and at Kettering [SP 9235 8687] a well through 2.1 m of Upper Lincolnshire Limestone over the Northampton Sands had a potential yield of 1818 m^3/d.

Effect of ironstone workings on the aquifer

The Northampton Sand was formerly worked extensively for iron in the Northampton-Corby district, and in south Lincolnshire (mostly to the south of Grantham). Open quarrying was used to remove the ironstone, often from beneath a thick overburden of Lincolnshire Limestone and Grantham Formation. The ironstone workings have had a profound and irreversible effect on the hydrogeological regime within the aquifer.

Water supplies from the Northampton Sand were generally unaffected by ironstone working as they are mainly drawn from the basal unworkable part of the formation. Consequently, areas where the ironstone workings were liable to cause a diminution of yield in existing wells or boreholes are probably limited. Similarly where the Lincolnshire Limestone is used as an aquifer, the ironstone is generally deeper than is practical for opencast working, and supplies are unlikely to be affected (Hollingworth and Taylor, 1951). These authors commented that future working of the ironstone in the Castle Bytham–Little Bytham area was likely to be affected by the distribution of underground water. Saturated areas such as the valley at Water Lane [SP 990 185] and immediately north of Little Bytham [TF 015 180] could prove difficult to work due to increased movement of water within the highly fissured overlying Lincolnshire Limestone along the valley bulge.

All workings are now defunct and more or less backfilled and restored. However, the impact of mining on water levels in the aquifer overall is significant, particularly in the north. This is due partly to increased recharge, and partly to the absence of dewatering operations associated with mining. This affects groundwater movement substantially and also creates the potential for groundwater pollution. Stanyer (1982) described the effects in the Corby area.

Prior to mining, much of the present outcrop of the aquifer was overlain by the Lincolnshire Limestone, Grantham Formation, or till; thus it received limited recharge. Water levels were relatively low, and the water table lay in the Northampton Sand aquifer. When mining started, natural recharge (directly at outcrop, via valley bulge, through channels in the Lincolnshire Limestone, and via leakage from the Lincolnshire Limestone) was supplemented by additional, anthropogenically-induced recharge (via infiltration through spoil material and directly through ironstone gullets[1]). Artificial recharge gradually increased until it became the principal source of water to the aquifer, with natural sources making up only a small percentage of the total recharge (Stanyer, 1982).

Many of the gullets have since been backfilled, preventing direct recharge to the aquifer, and this method of recharge is only likely to be a significant factor where such fractures locally remain open. Recharge from reclaimed areas occurs via infiltration through both the top soil and the underlying spoil, as is shown by the fact that it is necessary to underdrain the spoil. The grading of land during reclamation and its subsequent return to agriculture has meant an increase in runoff and evapotranspiration over that which occurred during mining, when pumping would have removed this water. Therefore at present, although the amount of recharge reaching the aquifer may be less than at the height of mining, it is far in excess of the original, natural recharge. The increase in recharge and removal of ironstone means there is more water available to flow through what is, in places, a thinner aquifer; for example beneath workings in the Corby area, only half the natural thickness of the formation remains (Stanyer, 1982).

During mining, dewatering caused local lowering of the water table around mining areas. Water table rebound has occurred since 1980. By October 1980 cessation of pumping caused an average reduction in flow to the Willow Brook of 11 700 m^3/d due to the loss of mine discharge water, and a further reduction of 21 000 m^3/d due to loss of the cooling effluent water. As a result of groundwater not being removed the aquifer was replenished, and found other outlets where it outcropped. During mining, groundwater from dewatering was discharged at Barnes Close Pumping Station and Priors Hall, and the springs at Weldon [SP 928 994] and Deene [SP 952 928] ceased flowing; within months of pumping stopping they were flowing again.

The increased amount of recharge, together with the cessation of dewatering, means that present day water levels are higher than those existing in the ironstone prior to mining. By 1982, the water level was at least partly in the overlying beds, with unconfined conditions beneath permeable spoil in the worked out areas, and confined conditions where overlain by impermeable deposits. In the Priors Hall North discharge shaft [SP 925 918 approximately], water levels rose at least 8 m in the two years after pumping ceased (Stanyer, 1982), the water level here being well within the spoil material which acted as a storage reservoir for the aquifer, accumulating infiltration and feeding the aquifer at a fairly constant rate. It has been observed that water levels can differ by 10 m in boreholes only a few metres apart (Stanyer, 1982). This is possibly related to the depth of the boreholes, as water levels are often recorded from wells open only in the lower half of the ironstone, while site investigation boreholes may only penetrate the top of the ironstone.

6.3.3.6 *Great Oolite Group*

Fuller's Earth Rock Member

Small supplies are obtained from the Fuller's Earth Rock, between the upper and lower clays of the Fuller's Earth Formation. A number of springs issue from its base, the clays below being impermeable. Clays may also act as internal confining layers. The Fuller's Earth also provides small supplies from the limestones or hard marls (e.g. Wattonensis Beds) within the upper clays in the south of the outcrop. Water is rarely encountered more than 30 m below surface.

There are very limited core or aquifer properties data. Two samples from a borehole at Winterbourne Kingston [SY 8470 9790] at a depth of around 750 m had porosities of 17.3 and 18%; the only hydraulic conductivity value was 6.0 $\times$ 10^{-4} m/d. An outcrop sample from the Dorset coast south of Burton Bradstock [SY 492 887] had a porosity of 5.3%.

A 168.6 m deep borehole at Stowell [ST 6849 2179] that finished in the Bridport Sands, yielded 110 m^3/d. The rubbly limestones of the Fuller's Earth Rock also yield small supplies of up to 35 m^3/d around Yetminster [ST 59 10]. Dug wells are generally more successful than boreholes.

Rutland Formation (formerly Upper Estuarine Series)

Again, there are few data on the aquifer properties of the Rutland Formation. In North Lincolnshire, 16 samples from one borehole at Nettleton Bottom [TF 1252 9820] at a depth of 344 to 371 m had a range of porosity values from 6.5 to 36.4% (Figure 6.26) and hydraulic conductivities varied from 3.8 $\times$ 10^{-6} to 0.37 m/d (Figure 6.27), reflecting the widely different lithologies present in the north Lincolnshire area (sands, silts and clays). The plot of hydraulic conductivity against porosity is shown in Figure 6.28.

The significant depth of the Rutland Formation in the Nettleton Bottom borehole means that these figures and graphs should be used with caution, as they may not be representative of the properties of the aquifer elsewhere, where it may be utilised at much shallower depths.

Great Oolite Limestone and equivalents

There are limited data available for this formation: a borehole at Milbourne Farm [ST 944 873] had a transmissivity

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[1] Gullets are defined as being tension fractures due to cambering.

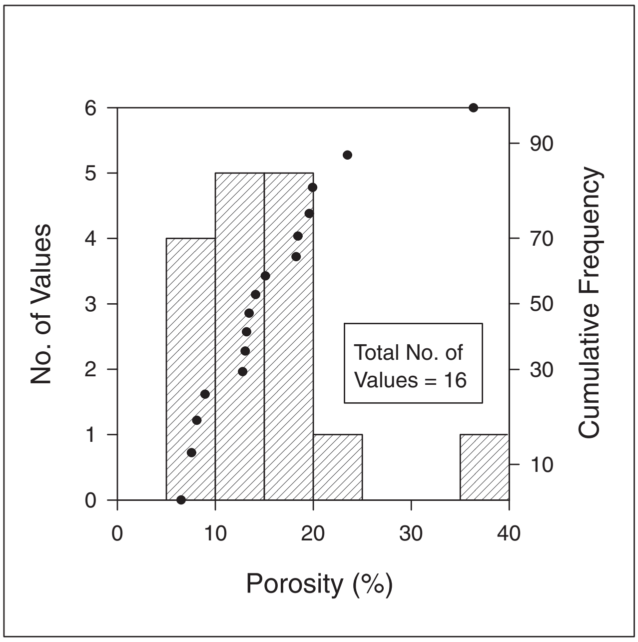

Figure 6.26 Distribution of porosity values for Rutland Formation samples.

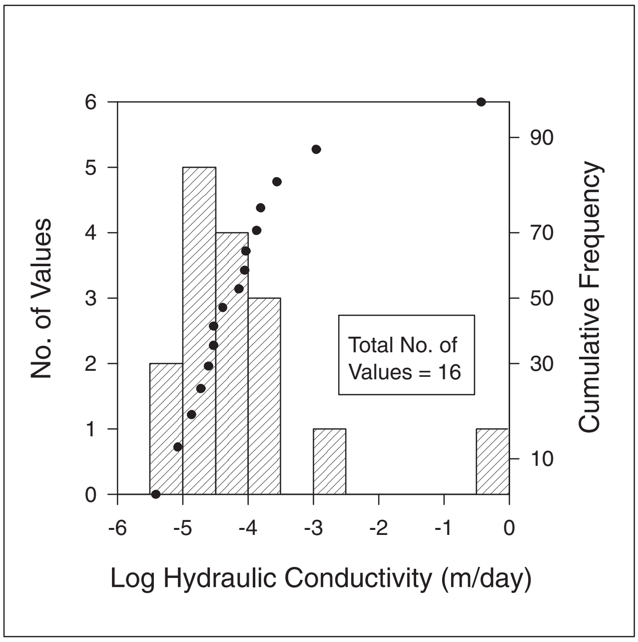

Figure 6.27 Distribution of hydraulic conductivity values for Rutland Formation samples.

of 35 m^2/d and a specific capacity of 20.6 m^3/d/m. A borehole at Lechlade Mill [SU 2289 9967] had a specific capacity of 9.7 m^3/d/m. South and east of Cirencester the Forest Marble Formation is part of the Great Oolite aquifer. Statistics of pumping test results for the Forest Marble are shown in Table 6.3.

The Blisworth Limestone and Cornbrash jointly are reported to feed springs in Lincolnshire (Johnson et al., 1999). In the Midlands, the Blisworth Limestone occurs at high elevations and is thin and hence tends to be dry. The thin useable zone, if exploited, is at the expense of rivers which, on the dip slope, are fed by springs. Where confined

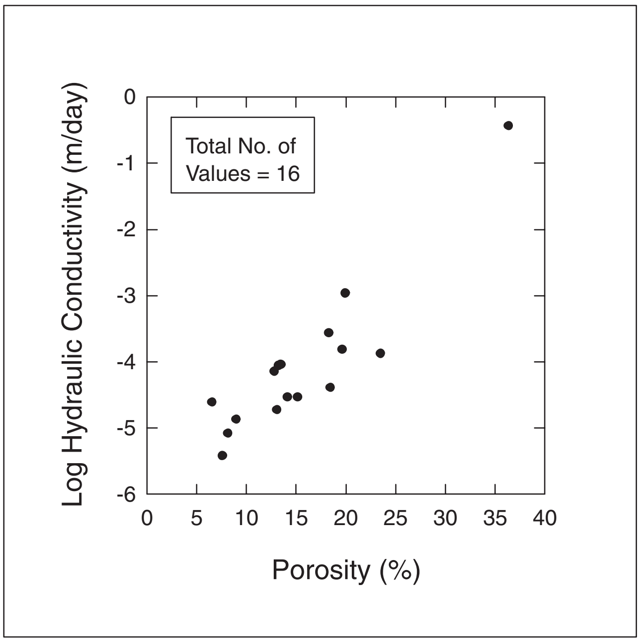

Figure 6.28 Plot of hydraulic conductivity against porosity for Rutland Formation samples.

the aquifer quickly tends to become saline. North of Oxford [SP 53 13], the Cornbrash, Forest Marble and Great Oolite resurface due to an anticlinal structure. In this area, some recharge is possible, and there is an extended area where they remain potable and small quantities of, often artesian, water are abstracted.

The limestone bodies of the Forest Marble Formation in the Wessex Basin include shell-banks and channel fills and have an unpredictable three dimensional form. Locally they may make up the greater part of the formation; elsewhere they may be virtually absent. Thus they do not form a laterally persistent, hydrologically continuous aquifer. The limestones are underlain by thick mudstone (basal Forest Marble and Frome Clay); locally they may be in continuity with the overlying Cornbrash.

In the southern part of the basin there are a few boreholes into the Forest Marble; yields are less than 40 m^3/d (Wilson et al., 1958). Wells into the Forest Marble and overlying Cornbrash at Radipole [SY 67 81] provided part of Weymouth's water supply (Arkell, 1947). The clays at the top create perched water tables in the Cornbrash. Further north the Forest Marble comprises medium hard, flaggy limestones with upper and lower clays; the latter give rise to springs at the junction with the overlying limestones. Exceptional initial yields of 430 m^3/d diminish to 40 m^3/d after a few days. A spring at Charlton Horethorne [ST 6722 2376] had a maximum yield of 250 m^3/d, others are less than 40 m^3/d. A borehole (112.8 m deep) at Henstridge [ST 7244 1989] yielded 85 m^3/d from beneath the Cornbrash. A shaft and borehole to a depth of 52.4 m at Templecombe [ST 7100 2272] yielded 120 m^3/d for 1.5 days for 10 m of drawdown, from an inflow at a depth of 25.3 m into the Forest Marble. Other boreholes have yields varying from less than 10 to 130 m^3/d, but some are dry.

There are two values for transmissivity from the Forest Marble in the Wessex Basin, at Liberty Farm [ST 556 083] and Caswell Farm [ST 581 098]; they are 2 and 25 m^2/d respectively. The two corresponding values for storage coefficient are 10^{-3} and 0.16. Specific capacities range from 8.6 to 115 m^3/d/m.

Cornbrash Formation

The Cornbrash provides small, perched groundwater supplies which tend to dry out during drought periods, especially if hydraulically separate from the Great Oolite Limestone or equivalents.

In the East Midlands Shelf area, the Cornbrash Formation is unimportant as an aquifer, due to its thinness and its separation from the underlying Blisworth Limestone by the Blisworth Clay. Mackay and Cooper (1996) quoted a Cornbrash field permeability measurement of 7.6 × 10^{-5} m/d at Elstow [TL 05 46] in Bedfordshire. A site at Caversfield [SP 586 250] had a specific capacity of 10.9 m^3/d/m.

In the Cotswolds, the Cornbrash typically forms extensive outcrops at the foot of the Cotswold dip slope where it is partly covered by terrace gravels. Hence it has both a large area and volume of recharge due to its hydraulic continuity with the rivers. Fairford was historically supplied by a spring from the Cornbrash at SP 1500 0130 and 3 m deep wells in the town centre whose water levels were related to those of the River Coln. Broughton Poggs [SP 23 04], was dependent on numerous shallow wells 3 to 4 m deep into Cornbrash in the past, which were of adequate quantity but doubtful quality. South of Cirencester the formation is thin and generally only provides small domestic and farm supplies from perched water above the Forest Marble, although a spring at Corston [ST 923 841] has a minimum yield of 2800 m^3/d (Cave, 1977).

Sen and Abbott (1991) obtained hydraulic conductivity and specific storage values from slug tests in the Cornbrash on both sides of a fault at Down Ampney [SU 117 963]. The curves were very steep and possibly represent the type of response described by Black (1985) for slug tests in fissured rocks where the early part of the curve represents the response of just the fractures, and the later part a transition to one where the storage in the matrix becomes more dominant. This would result in an overestimation of transmissivity and underestimation of storage. Certainly values for specific storage were much lower than could reasonably be expected in this type of oolitic limestone (around 5 × 10^{-22} m^{-1}). The values of hydraulic conductivity varied from 0.37 to 1.8 m/d. Using constant rate abstraction tests with a submersible pump, the hydraulic conductivity values were similar, varying from 1.0 × 10^{-2} to 1.9 m/d, and the specific storage ranged from 2.2 × 10^{-6} to 2.2 × 10^{-2} m^{-1} (using Jacob, Chow and Theis methods).

Results from responses during pumping tests in Cornbrash boreholes gave low values for hydraulic conductivity and high values for storage, compared to the results from observation boreholes. This could be caused by skin effects and the difficulty of defining an effective borehole radius for the analysis of the pumping test. The results showed differing aquifer properties on either side of the fault. Reasonable bulk values for Cornbrash hydraulic conductivity were considered to be 0.9 to 1.7 m/d on the upthrown side of fault and 0.3 to 0.9 m/d for the downthrown side. The differences could be due to natural variation, or different groundwater compositions resulting in varying degrees of dissolution or precipitation, which in turn have affected hydraulic properties.

From regional flow patterns Sen and Abbott (1991) anticipated that the heads would be artesian in both the Cornbrash and in the underlying Great Oolite Limestones beneath the Forest Marble clay. However, the measured heads were found to be considerably below the ground surface, while those in the Oxford Clay and Kellaways beds were artesian. This is possibly caused by abstraction of Great Oolite water at Latton and/or Meysey Hampton. These abstractions had been thought to be hydraulically isolated by faulting, but possibly they are not.

In the Wessex basin, the Cornbrash may locally be in continuity with underlying Forest Marble limestones. In the south of the basin, despite its narrow outcrop, it supplies up to 32 m^3/d from bores less than 18 m deep. Further north it yields small local supplies of up to 25 m^3/d from shallow wells and springs. A 9.1 m deep well, 1820 mm diameter, at Bishop's Caundle [ST 6998 1236] was fitted with a pump of 50 m^3/d capacity.

There is one porosity value of 5.8% from an outcrop south of Fleet [SY 630 798] on the Dorset coast.

6.3.3.7 *Kellaways Sand Member*

The Kellaways Sand of the East Midlands Shelf is not as good an aquifer as the Kellaways Rock of the Cotswolds or its equivalents in the Cleveland Basin. Porosities (for all areas) range from 4.3 to 37.6% (Figure 6.29), and hydraulic conductivities are typically 10^{-4} m/d but vary from less than the minimum measurable to 2.4 × 10^{-2} m/d. The porosity distribution (22 samples) taken from five boreholes is distinctly bimodal, showing that the formation ranges from moderately well cemented to practically unconsolidated, with numerous values in the range 30 to 38%. The fine grain size found in some horizons is reflected in a wide range of hydraulic conductivities.

East Midlands Shelf

The Kellaways Sand yields small supplies of groundwater. Hydraulic conductivity values are very low, partly due to the high fines content of the sands. No springs issue from its outcrop. Hydraulic heads are low, about 1 in 350, in the main part of Marston Vale. On a regional scale heads in the Kellaways Sand are generally above those in the underlying Blisworth Limestone, indicating downward flow from the sand to the limestone (Mather et al., 1998).

Excavated clay pits at Elstow in Bedfordshire [TL 05 46] represent local points of recharge to and discharge from Kellaways Sand through the thin residual layer of clay

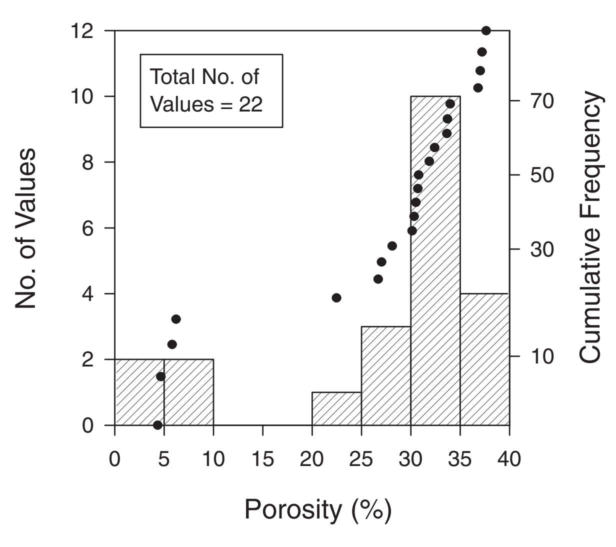

Figure 6.29 Distribution of porosity values for Kellaways Sand samples.

(Mackay and Cooper, 1996). Where the pit is filled with water (e.g. Stewartby Lake) recharge occurs to the Kellaways Sand through the base of the pit; thus near the pit, the Kellaways Sands have a higher potentiometric head than the Blisworth Limestone. Where the pits are empty, discharge from the Kellways Sands into the pits occurs, and the head in the Kellaways Sands is below that of Blisworth Limestone. The pits do not fill with water, as the volumes of groundwater involved are small compared with potential evaporative losses. Where the pits are filled with refuse that has subsequently become saturated, significant recharge to the Kellaways Sands occurs through the base of the pit.

Core samples from four boreholes into the Kellaways Sand gave porosity values varying from 5.8% at a depth of 13 m north of Stewartby [TL 0151 4410] to 38% at a depth of 39 m at Marston Vale [TL 035 403] (Figure 6.28). A single sample from a borehole at Nettleton Bottom [TF 1252 9820] at a depth of 317 m had a porosity of 26.7% and a hydraulic conductivity of 2.5×10^{-2} m/d. An outcrop sample at South Cave Station Quarry [SE 9189 3291] gave a hydraulic conductivity of 4.4×10^{-3} m/d. Mather et al. (1998) quoted a median hydraulic conductivity for the Kellaways Sand of the area south-west of Bedford of 2.7×10^{-2} m/d. Mackay and Cooper (1996) quoted field hydraulic conductivities in the range 1.1×10^{3} to 2.1×10^{-2} m/d, vertical laboratory values of 2.4×10^{-3} to 3.5×10^{-6} m/d and horizontal laboratory values of 1.3×10^{-5} to 1.0×10^{-2} m/d. Mather et al. (1998) concluded that the sand would not yield water to pumping wells at a useful rate as for a 5 m thick aquifer his median hydraulic conductivity value gives a transmissivity of 13 of 0.13 m/d

Mackay and Cooper (1996) carried out modelling using permeabilities of 86 m/d to 8.6×10^{-2} m/d and a porosity of 6%. They concluded from modelling the failure of a notional shallow waste repository in the former brick pits overlying the Oxford Clay, that the Kellaways Sand Formation would provide the principal conduit for any long-range, advectively dominated, contaminant migration that might occur. Long-range migration was unlikely to occur if the nearby brick industry excavations in the Oxford Clay were backfilled. In this case the vertical hydraulic gradients would be reversed, resulting in upflow to the ground surface. Mather et al. (1998) on the other hand argued that an engineered containment system at the base of the brickpits excavated into the Lower Oxford Clay was unnecessary, taking the view that the Kellaways Sand was not to be considered a productive aquifer. The rationale was based on the low permeability of the formation due to its high fines content, and also due to the fact that chloride ion concentrations rendered the water non-potable.

Cotswolds

The Kellaways Sand Formation provides yields of local significance from shallow to moderate depth wells in the area between Seagry [ST 96 81] and Christian Malford [ST 96 79] (Osborne White, 1925). Further north-east, it maintains approximately the same thickness, but comprises generally less well cemented, very fine-grained sands, and is probably of less significance as an aquifer, providing less than 85 m^3/d of poor quality, often saline, water from springs and shallow wells.

Locally, faulting must place the Kellaways Sand and the Cornbrash (beneath the Kellaways Clay) in hydraulic continuity. The Kellaways Sand tends to occur at the foot of the Cotswolds dip slope; hence in the Thames valley much of the outcrop is beneath and in continuity with the terrace gravels and thus (presumably) with the river.

The samples from the Kellaway Sands in this area provided porosity values ranging from 4.3 to 34% and hydraulic conductivity values ranging from 5.5×10^{-6} m/d to 1.4×10^{-3}. These analyses were determined for samples originating from a deep borehole at Harwell [SU 4680 8644] at depths of between 325 and 335 m.

No information is available on the hydraulic properties of the Kellaways Sand in the Wessex Basin.

6.3.3.8 *Corallian Group*

Humberside to east Oxford

As described in Section 6.3.2.10 there are only two minor limestones within a thick argillaceous Corallian sequence in this area.

BRANTINGTON FORMATION

North-east of Brough, the Brantingham Formation is faulted against, and likely to be in hydraulic continuity with the Kellaways Sand. North of the Humber, boreholes near Melton [SE 972 256] tap the Brantingham Formation/ Kellaways Sand as well as the Cave Oolite below. Saline intrusion has been induced, the extent varying according to abstraction rates and recharge. Chloride concentrations reached 1700 mg/l in the upper aquifer in the past, but have since been steadied at 100 to 200 mg/l (Gaunt et al., 1992).

WEST WALTON FORMATION

Two parts of the West Walton Formation are minor aquifers; the Upware Limestone and the Elsworth Rock. The Upware Limestone provides small brackish supplies. The Elsworth Rock Group was locally of importance in the past for small domestic and farm supplies, but is no longer much used (Edmonds and Dinham, 1965). There are a number of small springs along the outcrop; examples are Nill Well near Yelling [TL 267 627] which is iron-rich and Holywell near St Ives [TL 336 708].

South Midlands

In the south Midlands, the Corallian Group is of variable lithology, but shallow carbonate facies predominate. The group comprises a sequence of minor aquifers, of which the Coral Rag is the most permeable. Springs occur on the scarp slope close to the Corallian and Oxford Clay junction, associated with landslips in the underlying clay. Springs also issue from the silty sands at the base of the Corallian, due to the change in permeability between the overlying Coral Rag and Highworth Grit and these basal beds. On the dip slope, springs occur at the junction of the Coral Rag with the overlying Kimmeridge Clay. These dip slope springs are supersaturated with calcium carbonate and deposit tufa, producing calcareous fens with unusual lime-loving vegetation assemblages which are protected as SSSIs, for example, Marcham Fen [SU 467 797]. The dip slope springs are utilised as farm catchpits around Swindon. In order to protect the springs from depletion, there are no longer any borehole abstractions in the Swindon area. North-eastwards, there are abstractions around Shrivenham, and several other villages such as Longcot (sited on the Kimmeridge Clay) abstract from the full saturated thickness of the Corallian. Where the Red Down Clay is present, a further spring line is developed at the base of the Red Down Sand, and dug wells into the sand historically utilised this water. However now only the Coral Rag and underlying parts of the aquifer are utilised. The aquifer is a major source of supply in the Abingdon area, with yields of up to 800 m^3/d. Springs also occur at the junction with the underlying West Walton Formation to the north-east. Also to the north-east, between Oxford and Thame, the Red Down Beds are absent and the aquifer is relatively unimportant compared with the area to the south-west; the only significant abstractions are from the confined part of the aquifer around Oxford.

The aquifer is affected by major faults and periclinal structures east of Oxford (Wheatley Fault Zone). These faults may have had a component of Jurassic movement which controlled the deposition of the Corallian; they now affect groundwater flow.

Downdip in the confined aquifer overflowing artesian conditions occur. However, aquifer usage is restricted as the quality deteriorates within a couple of kilometres with increases in salinity to beyond the potable standard, due to the presence of connate water. Evidence from interstitial pore-water chemistry suggests the position of the mixing zone has migrated with time and the balance point is sensitive to both recharge to, and abstraction from, the Corallian.

At Wootton [SP 4811 0063] the Corallian yields 660 m^3/d and is used for public supply (Richardson et al., 1946). A maximum yield of 1425 m^3/d was obtained at Cowley [SP 5513 0311], from a 250 mm borehole for a drawdown of 2.2 m but more typical yields are 25 to 85 m^3/d, and less where the aquifer is not fully saturated (Horton et al., 1995). At Shillingford [SU 5956 9293] a borehole struck water in the Corallian beneath Gault, Lower Greensand and Kimmeridge Clay at 114 m, which rose to within 18 m of the surface. It was potable, but of insufficient quantity. The Lower Greensand water above was saline (Jukes-Browne and Osborne White, 1908).

In the south-west, around Marlborough, the Corallian is less important as an aquifer than might be inferred from the permeable nature of the beds and the extent of the outcrop. Recharge quickly finds its way to small springs along the deeply indented Corallian boundary. It is a poor aquifer around Hilmarton [SU 02 75] (Osborne White, 1925). At Wootton Bassett [SU 0775 8155] springs from the Coral Rag with a head of 8 m force themselves up to the surface through the Ampthill Clay (Bristow et al., in press).

Alexander and Brightman (1985) studied the Corallian of the south Midlands. Water quality becomes highly mineralised within a few kilometres of outcrop, with some vertical flow occurring through the Gault Clay Formation, Kimmeridge Clay and Oxford Clay. At Harwell, south Oxfordshire [SU 4680 8644] both potable and non-potable groundwaters occur in the Corallian strata. Based on chemical, stable isotope and radioisotope data, drilling, and the monitoring of pressure heads, they proposed that the groundwater flow pattern involves two subsystems. In the north-west recharge from outcrop flows south-east downdip; in the south the elevated topography of the Chalk produces cross-formational recharge which moves updip towards the north-west. The two systems meet in a region of low hydraulic head centred on Abingdon and extending west along the Ock valley. Here mixing takes place, and some discharge occurs through the Kimmeridge Clay. Therefore older more saline waters flow updip towards the edge of the Kimmeridge Clay, whilst more recent fresh recharge waters in the north flow downdip towards the River Ock. The zone of mixing of these two systems is located just under the edge of the Kimmeridge Clay. The presence of both saline and freshwater can be attributed to the laterally variable nature of the Coral Rag and Lower Calcareous Grit. This results in the interdigitation of materials with varying properties and varying water chemistry/density, which change relative to the balance point between the two opposing fluid circulation patterns. This conceptual model explains the observed groundwater quality variations in the Corallian of the Thames valley.

AQUIFER PROPERTIES DATA

The limited data available (11 analyses from a borehole at Harwell [SU 4680 8644]) are shown in Table 6.2. They indicate that the porosity of the limestones is highly variable, ranging from 6.0 to 39.3% with a mean value of 23.7% (Figure 6.30), probably indicating variations in both the degree of cementation and clay content. The hydraulic conductivity values also span a wide range (2.5×10^{-5} to 1.4×10^{-2} m/d) (Figure 6.31). In general higher permeability and porosity values correspond, with low values of both representing a higher clay content (Figure 6.32).

There is one site with pumping test data, at Marcham [SU 4626 9736], penetrating 12 m of sandstone and limestone; the storage coefficient was 6×10^{-4}, and the transmissivity 700 m^2/d.

Specific capacity varies from 4 to 2200 $m^3/d/m$, with a geometric mean value of 54 $m^3/d/m$ (Table 6.3 and Figure 6.33).

Wessex Basin

Typically, in this area the Corallian forms a multilayered aquifer, the permeable horizons being separated by confining layers. Artesian conditions are common, as evidenced by springs and overflowing bores. The individual limestones and sandstones are thin. Storage is limited and yields are relatively low, around 85 to 170 m^3/d from springs and shallow wells and often less than 40 m^3/d from 150 mm diameter bores. For example a six day test on a 152 mm diameter and 52 m deep bore at Mappowder Court [ST 7384 0585] yielded 40 m^3/d for 45.7 m drawdown from a sequence from the Clavellata Beds down to the Hazelbury Bryan Formation. Water was struck at 30.5 and 45.7 m in the Hazelbury Bryan Formation and rose to 1.5 m from surface (Bristow et al., 1995).

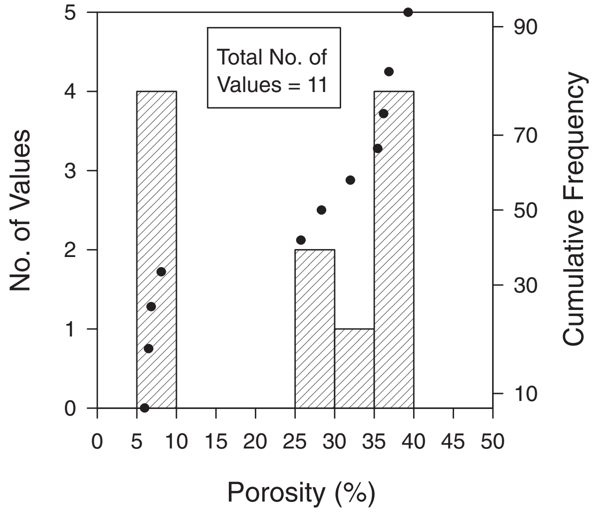

Figure 6.30 Distribution of porosity values for Corallian samples from the south Midlands.

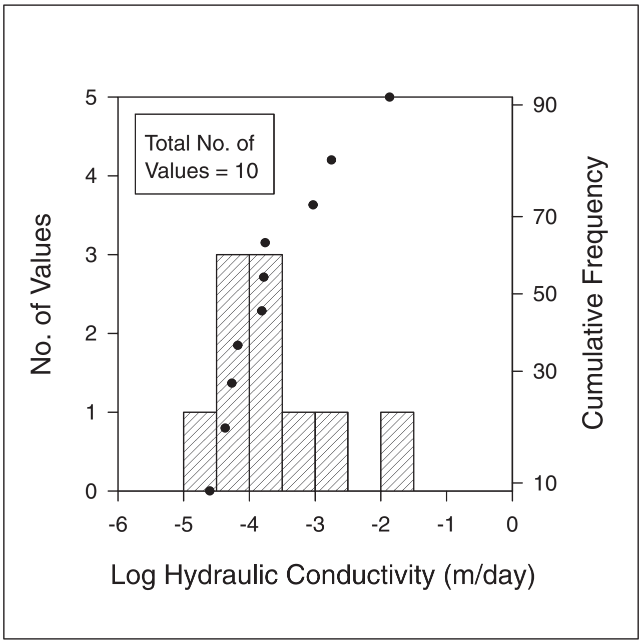

Figure 6.31 Distribution of hydraulic conductivity values for Corallian samples from the south Midlands.

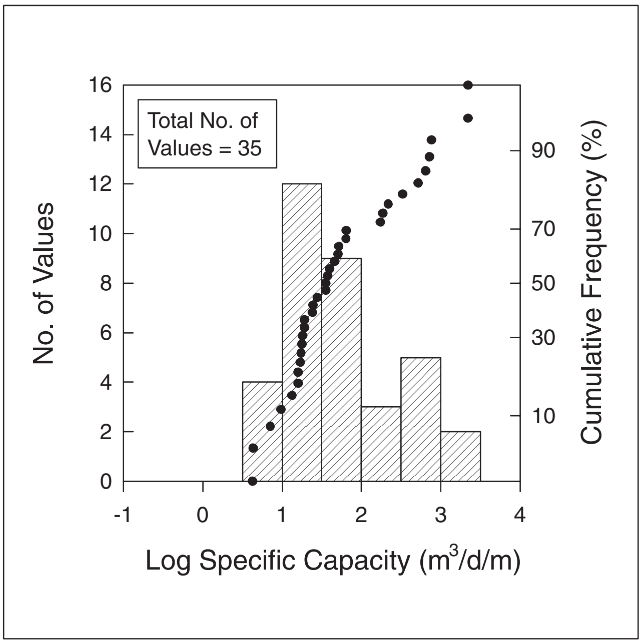

Figure 6.33 Distribution of specific capacity values for the Corallian in the south Midlands.

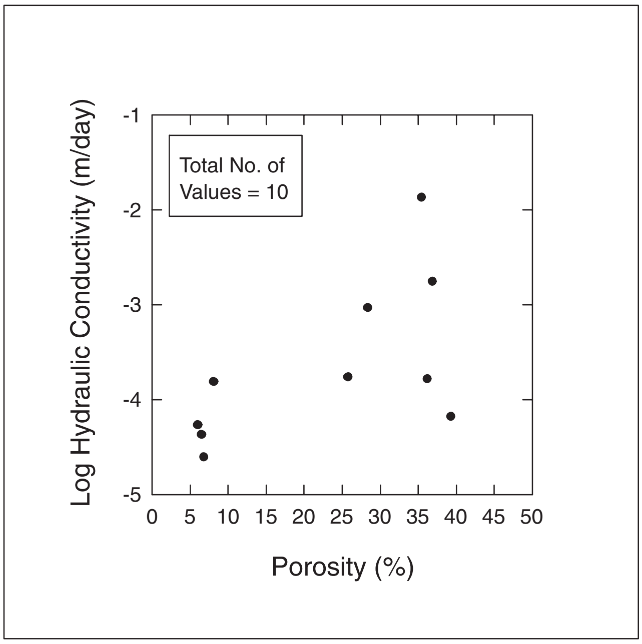

Figure 6.32 Plot of hydraulic conductivity against porosity for Corallian samples from the south Midlands.

The Nothe Grit Formation (Hazlebury Bryan Formation) forms the thickest and best aquifer of the Corallian Group in the Shaftesbury area. The highest yield is 490 m^3/d for 3 hours from an 1800 mm diameter well, 6 m deep at Sturminster Newton [ST 7888 1428], probably reaching the Hazelbury Bryan Formation. Another borehole also from the Hazelbury Bryan Formation (203 mm diameter and 24 m deep) at Holnest Park [ST 6528 0897] yielded 112 m^3/d for a day, for no observable drawdown.

Weymouth originally obtained water from a well near Rodwell House sunk through the Nothe Clay into the Nothe Grits (Arkell, 1947), and also a well was used in the Corallian at Broadwey, together with springs from the Corallian at Broadwey and Wyke.

Around Gillingham [ST 80 26] several industrial supplies are obtained, with the Coral Rag and Sandsfoot Grit providing significant contributions. A borehole at the bacon factory in Station Road [ST 8086 2615] penetrating 14.9 m of Corallian yielded 1090 m^3/d for a drawdown of 2.3 m.

A borehole into the upper part of the Corallian (Sandsfoot Grit and Abbotsbury Iron Ore) at Dowerfield Dairy Farm, Long Bredy [SY 5616 9074] yielded 24 m^3/d (Wilson et al., 1958).

The three transmissivity values for the Corallian of this area range from 1 to 21 m^2/d and the six specific capacity values from 0.9 to 109 m^3/d/m (Table 6.3). Eight outcrop samples on the Dorset coast [SY 74 81] had porosities ranging from 2.2 to 13.8% (Table 6.2). Eighteen borehole samples from the Osmington Oolite discussed in Allen et al. (1997) had higher porosities (between 4 to 23%) and hydraulic conductivities of less than the minimum measurable to 9×10^{-2} m/d.

6.3.3.9 *Kimmeridge Clay*

Elsham Sandstone Formation

The Elsham Sandstone Formation is locally in hydraulic continuity with the overlying Chalk and Carstone. In South Humberside where the Chalk's water resources are fully committed, it is utilised locally for supplies (Gaunt et al., 1992). Further east it forms a thin, confined water-bearing unit, containing good quality sodium bicarbonate type water which is not currently used for supply (Berridge and Pattison, 1994).

Five pumping tests have been carried out on two boreholes. At Wooton Wold Farm, Ulceby [TA 053 153], where the sandstone occurs at a depth of 61 to 63 m beneath Chalk and Red Chalk, it had a mean transmissivity value of 9 m^2/d and a storage coefficient of 2×10^{-4}. At South Killingholme [TA 1562 1695], where the sandstone is at a depth of 180 m beneath the Chalk, the mean transmissivity was 21 m^2/d and the storage coefficient around 3 × 10^{-6}.

Kimmeridge Clay of Dorset

There are, again, limited data available for the Kimmeridge Clay of Dorset. The Main Oil Shale Band at Portesham [SY 6093 8557] gave an initial yield of 1200 m^3/d from a shaft. A 305 mm diameter borehole 39 m deep at Stoke Wake [ST 7574 0680] yielded 120 m^3/d for three hours from the Kimmeridge Clay in 1947. It later collapsed, was cleaned out and relined and became dry in 15 minutes when pumping at between 78 and 85 m^3/d. Kimmeridge Clay water contains iron and often has a high total dissolved solids content (Bristow et al., 1995).

6.3.3.10 *Portland and Purbeck groups*

Upper Jurassic and Lower Cretaceous outliers of the south Midlands

Where present these beds can all logically be regarded as part of the same aquifer system. They rest on Kimmeridge Clay, giving rise to a spring line (such as at Brill [SP 655 140] and Long Crendon [SP 695 085]) and cambering phenomena. They are overlain in many places by the Lower Greensand Group. Groundwater movement is generally intergranular with some fracture flow in the limestone horizons. The outliers occurring on high ground drain rapidly and hence have a thin saturated thickness. At Spartum Fen [SP 654 016], water from the Portland and Lower Greensand Groups rises through a small window in the overlying and confining Gault Clay Formation. However the chemistry of the water, with a predominance of calcium and carbonate ions, implies that most comes from the Portland Group.

AQUIFER PROPERTIES DATA

The six specific capacity values for four boreholes probably all into the Portland sand in the area between Great Haseley [SP 63 01] and Thame [SP 72 06], varied from 1.9 to 879 m^3/d/m, with a geometric mean of 47 m^3/d/m.

At Spartum Fen [SP 654 016] the hydraulic conductivity of the aquifer (from rising head tests) was 0.3 m/d for the uppermost horizons and 10 m/d for the bulk of the aquifer. The maximum summer flow to the fen is 100 m^3/d (V Robinson, personal communication).

Yields are very variable and generally quite small, 8 to 170 m^3/d, often for appreciable drawdowns. However at Thame [SP 7281 0605], four 250 to 300 mm diameter boreholes to the base of the Portland Group yielded between 95 and 800 m^3/d, the highest for only 0.9 m drawdown (Horton et al., 1995). Where in hydraulic continuity with the Lower Greensand Group, yields are generally greater than 80 m^3/d: 140 m^3/d was recorded for 1.6 m drawdown from a 114 mm diameter borehole at Emmington [SP 7403 0246].

Portland Sand Formation of southern England

On the Isle of Portland, the Portland Sand is separated from the limestones of the Portland Limestone Formation by the Portland Clay at the base of the latter, but further east on Purbeck this is absent and the ‘sands’ and limestone are in hydraulic continuity. The water in the Upwey Wishing Well [SY 6614 8526] comes mostly from the Chalk, although the spring issues at the junction of the Portland Stone and the overlying Lower Purbeck.

Nine samples from a borehole in the Weald at Fairlight [TQ 8592 1173] at depths of between 341 and 352 m had porosities ranging from 3.3 to 16.2% and hydraulic conductivities from less than the measurable minimum to 1.8 × 10^{-4} m/d. Four outcrop samples from Hounstout Cliff [SY 9530 7719] had porosities varying from 16 to 23%. The overall porosity distribution is shown in Figure 6.34.

Minor springs issue from the Portland Sand. Boreholes only draw from the base of the Portland Sand; as the catchment area is so limited, yields are low. A well and bore at Southwell [SY 6834 7018], sunk 82 m with 40 m of headings at a depth of 67 m produced 409 m^3/d of water from the sands 1.1 m below sea level. The overlying Portland Stone was dry. The water was contaminated by sea water and sewage (Arkell, 1947).

Purbeck Group of southern England

The Purbeck of the Weald consists of shales with horizons of limestone, sandstone and gypsum. The limestones contain water of limited importance for supply, as their outcrop is very limited. However, water from the fractured limestones enters the gypsum mines and pumping rates of 850 m^3/d have been recorded (Lake and Shephard-Thorn, 1987). The water is very hard due to its contact with the limestone and gypsum.

Five samples from a borehole, into the Lulworth Formation, off the Isle of Wight [SZ 8197 3944], at depths of between 8 and 51.5 m, had porosities ranging from 17.1 to 34.5% and hydraulic conductivities between 2.0 × 10^{-3} and 1.0 m/d. Four outcrop samples from the Dorset coast had porosities varying from 1 to 12%.

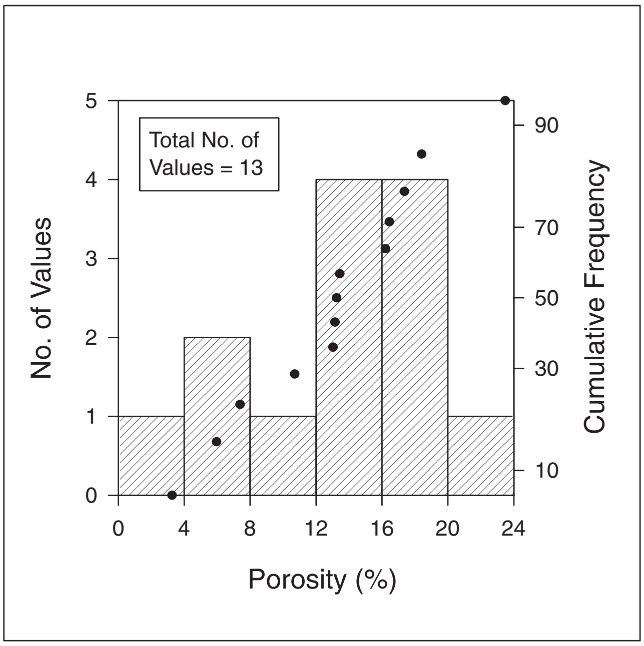

Figure 6.34 Distribution of porosity values for Portland Sand samples.

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7 Permian and Triassic minor aquifers

7.1 INTRODUCTION

The Permo-Triassic sandstones of England and Wales constitute a major aquifer which is second only in importance to the Chalk of southern and eastern England. The aquifer characteristics of those sandstones have been described in detail in the companion volume to this publication (Allen et al., 1997).

The extensive deposits of Permian and Triassic age rocks in England and Wales do however include thick successions of mudstones with subordinate siltstones and sandstones. These are predominantly impermeable or of low permeability and are commonly only considered as aquicludes or aquitards. As such they form the upper or lower limit of much more permeable sandstone and conglomerate aquifers. One example is the Aylesbeare Mudstone Group which separates Permian and Triassic sandstone aquifers in south-west England. Another is the Mercia Mudstone Group, a thick marl sequence overlying the Triassic Sherwood Sandstone Group aquifer throughout England and Wales. Although rarely capable of producing large yields, these two thick mudstone sequences can constitute minor aquifers in their own right by virtue of the subordinate fractured sandstone horizons they contain. These locally provide limited supplies of water. The Permian and Triassic mudstone sequences therefore constitute minor aquifers of considerable, though geographically limited importance in several parts of England and Wales. Their hydrogeological characteristics and properties are described below.

7.2 THE AYLESBEARE MUDSTONE GROUP

7.2.1 Introduction

The Aylesbeare Mudstone Group crops out in a generally north–south trending belt extending from the Lyme Bay coast at Exmouth, east of Exeter towards the north Somerset coast at Watchet (see Figure 7.1). The group overlies the Exeter Group, which consists of conglomerates, breccias and sandstones of Lower Permian age. To the east of the outcrop, the Aylesbeare Mudstone Group dips gently beneath the Budleigh Salterton Pebble Beds, the lowest formation of the Sherwood Sandstone Group in east Devon.

7.2.2 Geology and stratigraphy

The Aylesbeare Mudstone Group is a mainly argillaceous succession consisting predominantly of reddish-brown mudstone but with beds of red or green sandstone common in the lower half. Recent mapping by the BGS in the Exeter area (British Geological Survey, 1995) aided by offshore data (Hamblin et al., 1992) suggests that the Group is entirely of Early Triassic (Scythian) age. This is the current BGS stratigraphic interpretation. Both the lower and upper boundaries of the Aylesbeare Mudstone Group are marked by minor unconformities.

7.2.2.1 *Extent of aquifer group, stratigraphy and lithology*

The group reaches a maximum thickness of about 500 m at Exmouth, progressively thinning to about 400 m east of Exeter, then more rapidly northwards to eventually pinch out in north Somerset. The group has been proved to thicknesses of at least 600 m downdip in Dorset and to over 1000 m beneath the English Channel. South-east of Exeter, two subdivisions, the Littleham Mudstone and the underlying Exmouth Sandstone and Mudstone Formation, have been recognised within the group.

Exmouth Sandstone and Mudstone Formation

This unit makes up the lower half (thickness approximately 250 m) of the group in the Exmouth area. It consists of reddish brown mudstone interbedded with red or grey-green, cross-stratified sandstone. Individual sandstone beds are lenticular in geometry and probably constitute the infills of fluvial channels, the interbedded mudstones representing the deposits of adjacent floodplains.

Littleham Mudstone Formation

This unit predominantly consists of structureless reddish brown mudstone with subordinate thin beds of silty sandstone. It forms the upper half (thickness approximately 250 m) of the Aylesbeare Mudstone Group near Exmouth. The depositional environment of the unit is considered to have been playa mud-flats, with the thin sandstone beds being deposited by occasional floods.

The sandstones in the lower part of the group die out rapidly northwards, and the subdivisions are no longer distinguishable to the north of Aylesbeare. Further north still, in the Clyst Hydon area, the lowermost 30–50 m of the group consists predominantly of reddish brown silty sandstone and sandy siltstone. These beds, recently named the Clyst St. Lawrence Formation (British Geological Survey, 1995), again provide a more arenaceous character to the lower part of the group.

Around Taunton the Vexford Breccias are present beneath the Aylesbeare Mudstone Group, which is here considered to be solely represented by the Littleham Mudstone Formation (Edmonds and Williams, 1985). The Vexford Breccias are 20 to 40 m thick and comprise fragments of sandstone, slate and quartz in a sandy matrix. These are in hydraulic continuity with the underlying Exeter Group and were grouped with them by the Institute of Geological Sciences and the South-west Water Auhtority (1982).

7.2.2.2 *Structural geology*

Regionally, the group dips gently towards the east at angles of between five and ten degrees. Low amplitude, eastward-plunging folds locally produce dips towards the north-east or south-east. Although few faults have been identified on the outcrop, more extensive, mainly east–west trending faults have been mapped in the adjacent outcrops of the Exeter Group and Budleigh Salterton Pebble Beds, such that much of the eastern edge of the group's outcrop is fault-controlled

Figure 7.1 Outcrop of the Aylesbeare Group in Devon and Somerset.

(see Figure 7.1). Local structural movements created the downfaulted Crediton and Tiverton troughs resulting in deposition of 200 to 800 m of Permian sediments. The seeming absence of similar faulting in the Aylesbeare Mudstone Group is therefore likely to be more apparent than real, arising from the difficulty in identifying faults within thick mudstone successions which lack distinctive, mappable marker beds.

7.2.3 Hydrogeology

7.2.3.1 *Introduction*

The Aylesbeare Mudstone Group is generally considered to act as an aquiclude, forming the base of the Sherwood Sandstone major aquifer system and confining the sandstone, conglomerate and breccia aquifers of the underlying Exeter Group. Hence it separates the two major groundwater systems of south-west England. Nevertheless, the Aylesbeare strata support many minor groundwater abstractions across the outcrop area, and the large number of small private sources ensures that the total volume of groundwater abstraction is of some significance. Due to its significant position between the major aquifers of the Exeter and Sherwood Sandstone groups, the Aylesbeare Mudstone Group has been briefly described in Allen et al. (1997), from which Table 7.1 is reproduced.

The quality of water from the Aylesbeare Mudstone Group is variable, with high total dissolved solids reflecting the presence of evaporite layers in the group and the immobility of much of the interstitial water. Groundwater is usually potable, but iron, sodium, chloride and sulphate concentrations may exceed EC guidelines.

Data held in the Aquifer Properties Database indicates that the rest water level in the Aylesbeare Mudstone Group is usually less than 10 m below ground level, although it may be as much as 30 m. Davey (1981) reports that seasonal water level fluctuations may be in excess of 5 m.

Table 7.1 Permo-Triassic stratigraphy in south-west England (from Allen et al., 1997).

Age	Group	Formation	Lithology	Thickness (m)	Aquifer unit
TRIASSIC	Mercia Mudstone		Mudstone, siltstone	360	Aquitard
	Sherwood Sandstone	Otter Sandstone	Sandstone	100–170	Aquifer
		Budleigh Salterton Pebble Beds	Sandstone, conglomerate	20–30	
	Aylesbeare Mudstone	Littleham Mudstone	Mudstone	70–530	Aquitard
PERMIAN	Exeter	Exmouth Mudstone and Sandstone	Mudstone, sandstone		
		Numerous local names, including the Dawlish (Clyst) and Knowle sandstones, Cadbury, Bow and Crediton breccias	Breccias, sandstones	up to 1000	Aquifer

7.2.3.2 *Previous studies*

Systematic hydrogeological investigations of the Aylesbeare Mudstone Group appear to be limited to a single author, J C Davey, who conducted a hydrogeological study of the Permian aquifers of central and east Devon as the subject of a PhD thesis (Davey, 1981). This comprehensive and invaluable inventory is believed to comprise mainly field observations supplemented by 1979 Southwest Water Authority licensed quantity extracts. A subsequent paper by the same author (Davey,1989) provides further insights. Other data have been collated from the BGS National Well Record Archive and the Environment Agency licensed abstraction records to increase the total amount of information available for the Aylesbeare Mudstone Group.

7.2.3.3 *Groundwater flow*

The groundwater flow in the Aylesbeare Mudstone Group is controlled by the lithology of the formations, particularly the presence of sandstone units. Selwood et al. (1984) suggested that 60% of the Exmouth Sandstone and Mudstone Formation is comprised of sandstones whereas 90% of the Littleham Mudstone Formation is mudstone. Most of the groundwater movement is thought to be through fractures (Davey, 1989), which are likely to be more transmissive in the sandstones than in the mudstones. By implication therefore, the lower part of the group is likely to have a more active flow system where sandstones form a significant proportion of the succession, as is the case south-east of Exeter and near Clyst Hydon.

Water level contours (Figure 7.2) show groundwater movement to be predominantly westwards and south-westwards from a groundwater divide which is against the dip but mirrors the topography. Cross-bed flow against the regional dip contributes to the quite steep gradients observed in the group which are typically around 1 in 75. However, lithological control is no doubt predominant, and Davey (1989) has observed that the hydraulic gradient is much steeper in the less permeable Littleham Mudstone Formation than in the Exmouth Sandstone and Mudstone Formation: typically 0.02 to 0.04 in the former and around 0.008 in the latter (Davey, 1989).

7.2.3.4 *Core data*

No core permeability or porosity values are held in the BGS Physical Properties Database for the Aylesbeare Mudstone Group. Davey (1981) lists porosity results from seven poorly cemented sandstone samples at outcrop at one site [SY 038 971]. Mean porosities of 28% for medium–coarse sandstone (four samples) and 25% for fine–medium sandstone (three samples) are recorded. These may be unrepresentative for equivalent beds at depth as weathering at the surface to friable sandstone or even sand is reported. In the same study, although hydraulic conductivity values for the group were not available, Davey cites measurements from lithologically similar members further down the Permian succession (Clyst Sands) at the Starved Oak Cross exploration well-site north of Exeter. These ranged from 1.3 m/d for a medium-coarse moderately well-cemented sandstone to 0.00005 m/d for a well-cemented siltstone. If similar horizons exist within the Aylesbeare Mudstone Group, there may be scope for flow through the matrix as well as through fractures in the more friable sandstone horizons; equally clearly the more compact siltstones and mudstones are effectively impermeable in the absence of connected fracture systems.

7.2.3.5 *Pumping test results*

Pumping test results are held for 16 sites from the Aylesbeare Mudstone Group: of these, five are from the Littleham Mudstone Formation, four are from the Exmouth Sandstone and Mudstone Formation, and two are from the Clyst St Lawrence Formation. At the five remaining sites the Aylesbeare Mudstone Group has not been subdivided. Results are summarised in Table 7.2.

Eleven values of transmissivity are available (Figure 7.3), showing a wide variation from 0.44 to 275 m^2/d. However, the high values are exceptional, and the interquartile range is from 1.1 to 17 m^2/d. None of the five values in the Littleham Mudstone Formation exceed 50 m^2/d. No transmissivity values are available for the Clyst St Lawrence Formation.

As with the transmissivity, the 15 values of specific capacity do not show a normal distribution (Figure 7.4). Values range from 0.7 to 229 m^3/d/m, but similar to transmissivity,

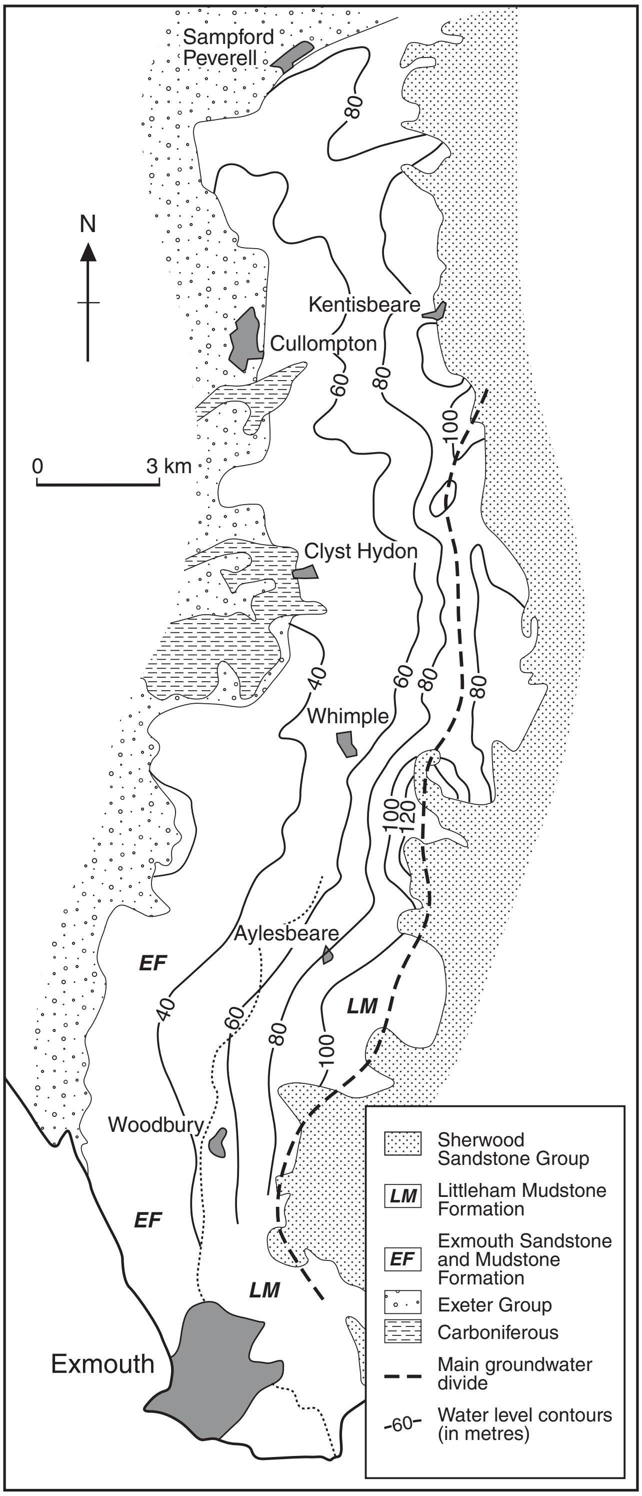

Figure 7.2 Water level contours for the Aylesbeare Mudstone Group.

the interquartile range is quite narrow, from 2.8 to 35.5 m^3/d/m.

A further small database which was consulted was the Environment Agency South-west register of current licensed abstractions as at September 1998. This contained 11 Permian aquifer entries of which five are in the Aylesbeare Mudstone Group. Transmissivities of 2 to 95 m^2/d were recorded with specific capacities of 3.4 to 216 m^3/d/m (arithmetic means of 38.4 m^2/d and 73.8 m^3/d/m respectively), similar to values on the Aquifer Properties Database.

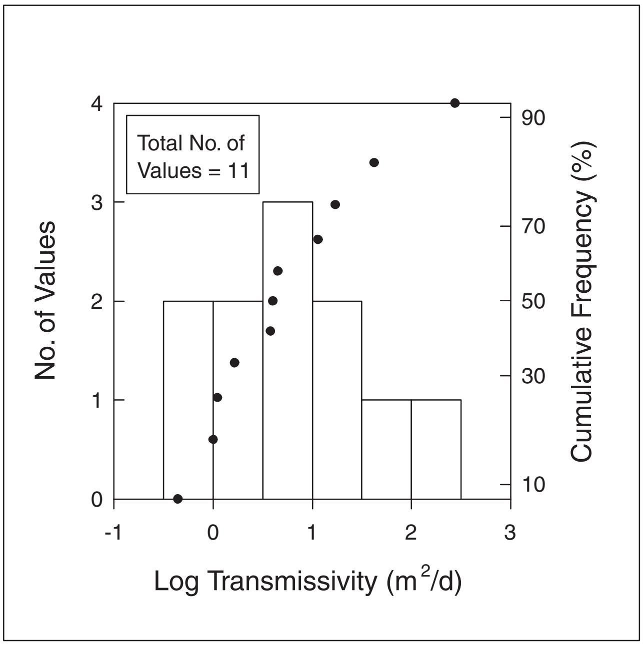

Figure 7.3 Distribution of all transmissivity values for the Aylesbeare Mudstone Group from the Aquifer Properties Database.

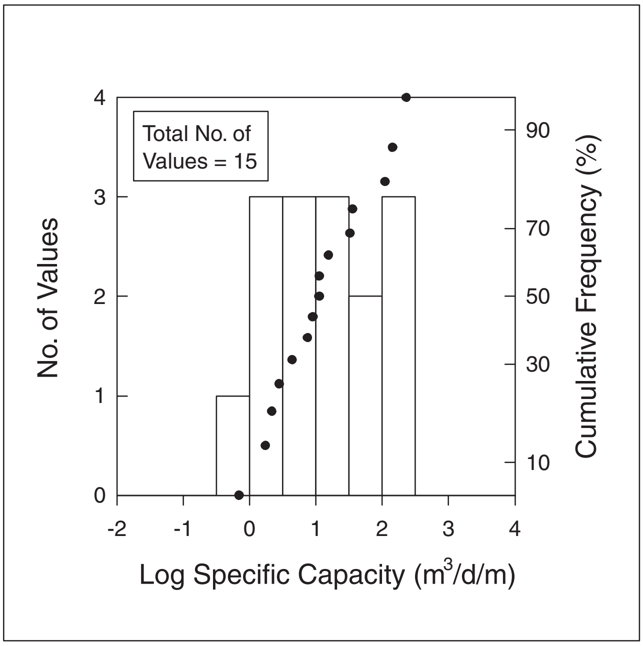

Figure 7.4 Distribution of all specific capacity values for the Aylesbeare Mudstone Group from the Aquifer Properties Database.

7.2.3.6 *Additional yield and specific capacity data*

Supplementary information on this data poor aquifer was collated from both the BGS National Well Record Archive (BGS-NWRA) and from Davey (1981). Specific capacities, yields and well depths were extracted from the former through the Wellmaster system. Complementary and overlapping yield and well depth information from Davey's PhD thesis are also provided for comparison. The results are summarised in Table 7.3 below and in Figures 7.5 to 7.8.

Table 7.2 Summary of aquifer properties data for the Aylesbeare Mudstone Group.

Aylesbeare Mudstone Group		
Total number of records	16	—
Number of transmissivity records	11	—
Minimum/maximum transmissivity value (m^2/d)	0.44	275
Arithmetic/geometric mean of transmissivity (m^2/d)	32.9	5.44
Median/interquartile range of transmissivity (m^2/d)	4	15.9
25/75 percentile of transmissivity (m^2/d)	1.1	17
Number of storage coefficient records	1	—
Minimum/maximum storage coefficient value	0.14	—
Number of specific capacity records	15	—
Minimum/maximum specific capacity ($m^3/d/m$)	0.69	229
Arithmetic/geometric mean of specific capacity ($m^3/d/m$)	41.0	12.1
Median/interquartile range of specific capacity ($m^3/d/m$)	11.2	32.7
25/75 percentile of specific capacity ($m^3/d/m$)	2.78	35.5

Table 7.3 Summary of specific capacity, yield and well depth information collated from BGS National Well Record Archive, and Davey (1981) for the Aylesbeare Mudstone Group.

Aylesbeare Mudstone Group		
BGS-NWRA data, 1998:		
Total number of sites	79	—
Number of borehole/well yield records	106	—
Minimum/maximum of borehole/well yield (m^3/d)	3.64	1137
Arithmetic/geometric mean of borehole well yield (m^3/d)	191	91.5
Median/interquartile range of borehole well yield (m^3/d)	87.3	214
25/75 percentile of borehole/well yield (m^3/d)	39.3	254
Number of spring yield records	10	—
Minimum/maximum spring yield (m^3/d)	1.73	691
Arithmetic/geometric mean of spring yield (m^3/d)	119	33.5
Median/interquartile range of spring yield (m^3/d)	43.2	134
25/75 percentile of spring yield (m^3/d)	5.18	139
Number of specific capacity records	72	—
Minimum/maximum specific capacity ($m^3/d/m$)	0.08	409
Arithmetic/geometric mean of specific capacity ($m^3/d/m$)	33.8	11.5
Median/interquartile range of specific capacity ($m^3/d/m$)	11.2	31.1
25/75 percentile of specific capacity ($m^3/d/m$)	4.42	35.5
Davey, 1981		
Total number of records	122	—
Number of borehole/well yield* records	97	—
Minimum/maximum of borehole/well yield* (m^3/d)	0.09	436
Arithmetic/geometric mean of borehole well yield* (m^3/d)	14.8	4.3
Median/interquartile range of borehole well yield* (m^3/d)	4.55	6.82
25/75 percentile of borehole/well yield* (m^3/d)	2.27	9.09
Number of spring yield* records	25	—
Minimum/maximum spring yield* (m^3/d)	0.45	364
Arithmetic/geometric mean of spring yield* (m^3/d)	20.3	4.49
Median/interquartile range of spring yield* (m^3/d)	4.55	7.39
25/75 percentile of spring yield* (m^3/d)	1.7	9.09

* May be licensed quantity or recorded yield

Comparison of results

(i) BGS-NWRA, 1998: A moderately large specific capacity dataset shows a log-normal data distribution with an interquartile range of 5 to 35 $m^3/d/m$ and a geometric mean of 11.5 $m^3/d/m$. Borehole/well yields tend to show much more variability and a slightly positively skewed distribution, typically around 40 to 250 m^3/d with a geometric mean of 92 m^3/d. Ten springs were identified in the dataset; their yields tend to be lower, with an interquartile range of 5 to 140 m^3/d and a geometric mean of 33.5 m^3/d.

(ii) Davey PhD Thesis, 1981: Analysis of the yield entries suggests the data are drawn from a very different population to that of the BGS-NWRA dataset. Well and spring yields are similar, being typically about 2 to 9 m^3/d with geometric means of 4.3 and 4.49 m^3/d respectively, these values being an order of magnitude less than yields in the BGS-NWRA

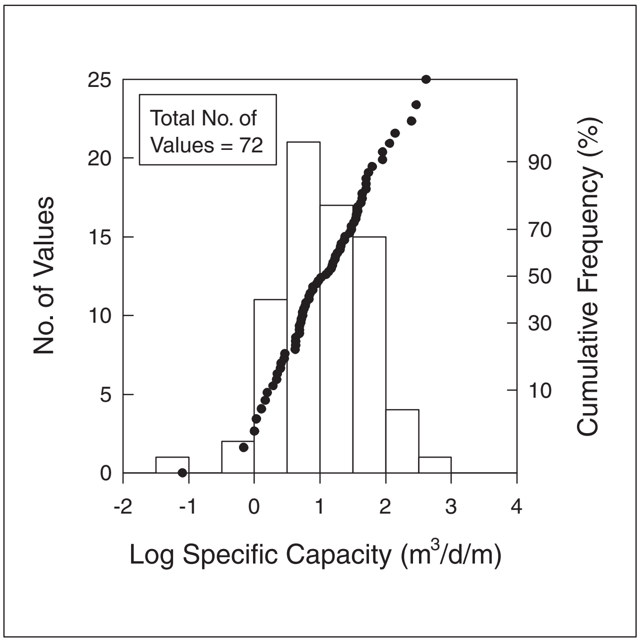

Figure 7.5 Distribution of borehole/well specific capacity values for the Aylesbeare Mudstone Group from the BGS NWRA database.

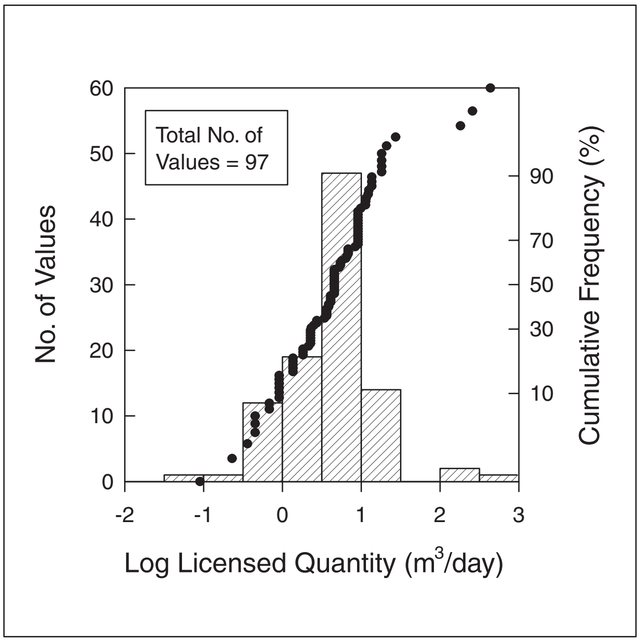

Figure 7.7 Distribution of borehole/well yield values for the Aylesbeare Mudstone Group from the Davey inventory (1981).

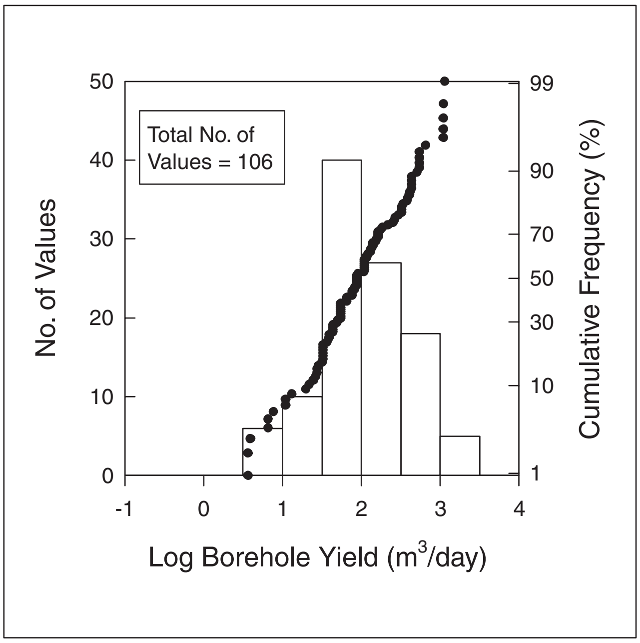

Figure 7.6 Distribution of borehole/well yield values for the Aylesbeare Mudstone Group from the BGS NWRA database.

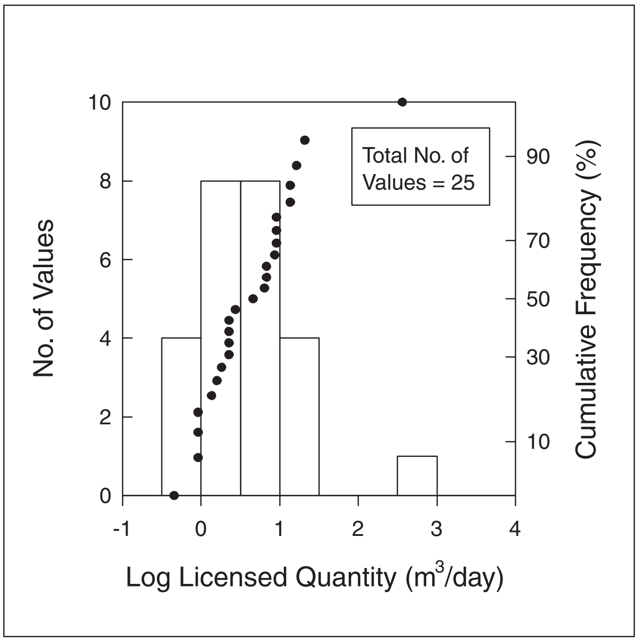

Figure 7.8 Distribution of catchpit/spring yield values for the Aylesbeare Mudstone Group from the Davey inventory (1981).

> dataset. The main reason is likely to be that the BGS well records contain a higher proportion of deeper boreholes, the Davey dataset being predominantly composed of wells less than 10 m deep (see Figure 7.9).

Edwards (1988) reported that most supplies from the Clyst St Lawrence Formation are taken from shallow wells, providing 0.8 to 28 m^3/d. However, two 30.5 m deep boreholes yielded 110 and 175 m^3/d on test pumping.

7.2.3.7 *Controls on permeability, transmissivity and yields*

The permeability and transmissivity of the aquifer are likely to be controlled by the presence of sandstone units; it would therefore be expected that higher values would be found for the more arenaceous Exmouth Sandstone and Mudstone Formation than for the Littleham Mudstone Formation. However, this supposition is not well supported by the available data, which shows little variability between the

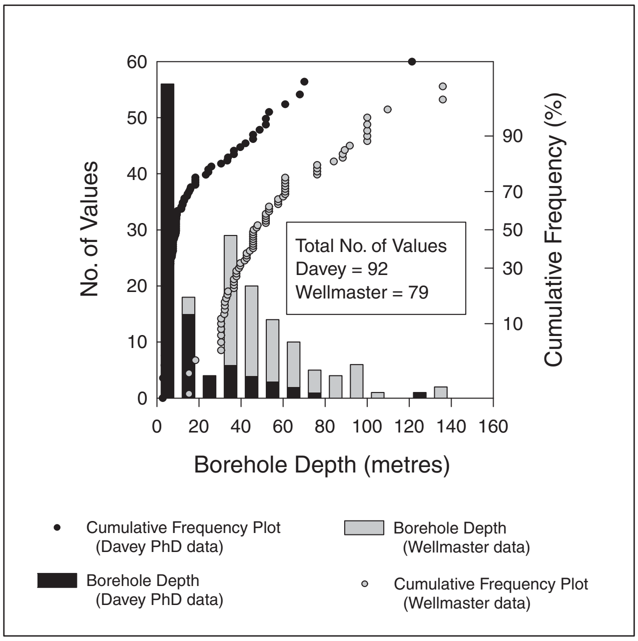

Figure 7.9 Comparison of well depths for the Aylesbeare Mudstone Group from the two principal data sources.

two formations. There is, however, some evidence of higher groundwater yields from the Clyst St Lawrence Formation than have been consistently obtained from the other two formations; the specific capacity values for the Clyst St Lawrence Formation are also high.

Davey (1989) also reported no discernible difference between pumping test values from the Littleham Mudstone and Exmouth Sandstone and Mudstone formations: specific capacity values for either formation ranged from 1 to 140 m^3/d/m. In his thesis, the same author also suggested .that there were four controls on the aquifer properties of the Permian aquifers of central and east Devon in general (and therefore by implication of the Aylesbeare Mudstone Group):

- the variation in lithology
- the degree of cementation
- the presence and interconnection of fracture zones
- the availability of other bodies of water (i.e. the potential for leakage-induced river recharge).

7.2.3.8 *Effect of superficial deposits*

Other than strips of thin alluvium and terrace deposits along river valleys, the outcrop of the Aylesbeare Mudstone Group is free of superficial deposits.

7.2.3.9 *Areal distribution of aquifer parameters/other relationships*

The yield data from the BGS-NWRA is shown in Figure 7.10 in comparison with the transmissivity and specific capacity results from pumping tests for the whole Aylesbeare Mudstone Group. No clear geographical trend along the strike is apparent, but there is a suggestion of rather higher yields to the west, where the lower part of the succession outcrops. The inference is that the lower part, where sandstone horizons are more common, may be more productive. This is consistent with Selwood et al. (1984) who reported that quantities that could be abstracted from the Littleham Mudstone Formation were much lower than from the Exmouth Sandstone and Mudstone Formation. Selwood et al. (1984) reported yields from a 90 m deep borehole in the Littleham Mudstone Formation not exceeding 55 m^3/d, although records of higher yields from the Littleham Mudstone Formation have been collected during this study, with the highest yield being 146 m^3/d.

7.3 MERCIA MUDSTONE GROUP

7.3.1 Introduction

The Mercia Mudstone Group, (formerly the Keuper Marl), has traditionally been regarded as predominantly impermeable and at best a poor aquifer. The group has therefore been most commonly referred to either in the context of forming a confining upper limit to the underlying Sherwood Sandstone Group aquifer or, rather less frequently, as the impermeable base of an overlying Quaternary unconsolidated aquifer (Edwards, 1997).

While effectively a non-aquifer in many areas, limited quantities of groundwater suitable for domestic or small scale agricultural use are, however, occasionally obtainable from the Mercia Mudstone. In some areas groundwater from the group represents the most important source of water in terms of the total number of licensed abstractions and geographic distribution, (for example in Worcestershire). These limited but valued resources are particularly important in areas where the evaporitic/basinal facies give way to buried topography fanglomerates, or where large thicknesses of mudstones are present over the Permo-Triassic sandstones. Under such circumstances it may not be viable to penetrate to the underlying sandstone aquifer, which in any case may contain poor quality water due to deep confinement.

The basal section of the group, consisting of mudstones together with siltstones and sandstones (Tarporley or Sneinton Formation) often forms a localised minor aquifer in its own right. Numerous small springs occur along the outcrop of this horizon and shallow wells have provided limited but adequate supplies to a clustering of old villages and farms which have arisen along the outcrop, for example in Nottinghamshire (Lamplugh et al., 1908). This basal unit of the group was formerly known as the Keuper Waterstones, reputedly due to their similarity in appearance to watered silk rather than their water bearing properties (Downing et al., 1970). In practice, few boreholes solely utilise this basal unit, most continuing to greater depth to penetrate the underlying Sherwood Sandstone aquifer. Higher in the sequence groundwater is usually obtained from the sandstone horizons present within a predominantly mudstone succession.

There have been no known previous hydrogeological investigations carried out specifically on the Mercia Mudstones, the group commonly only being discussed in the context of its association with the Sherwood Sandstone Group aquifer.

7.3.2 Geology and stratigraphy

7.3.2.1 *Extent of aquifer group, stratigraphy and lithology*

The outcrop of the Mercia Mudstone Group extends northwards from Lyme Bay through Somerset and on to both sides of the Severn Estuary (see Figure 7.11). It then

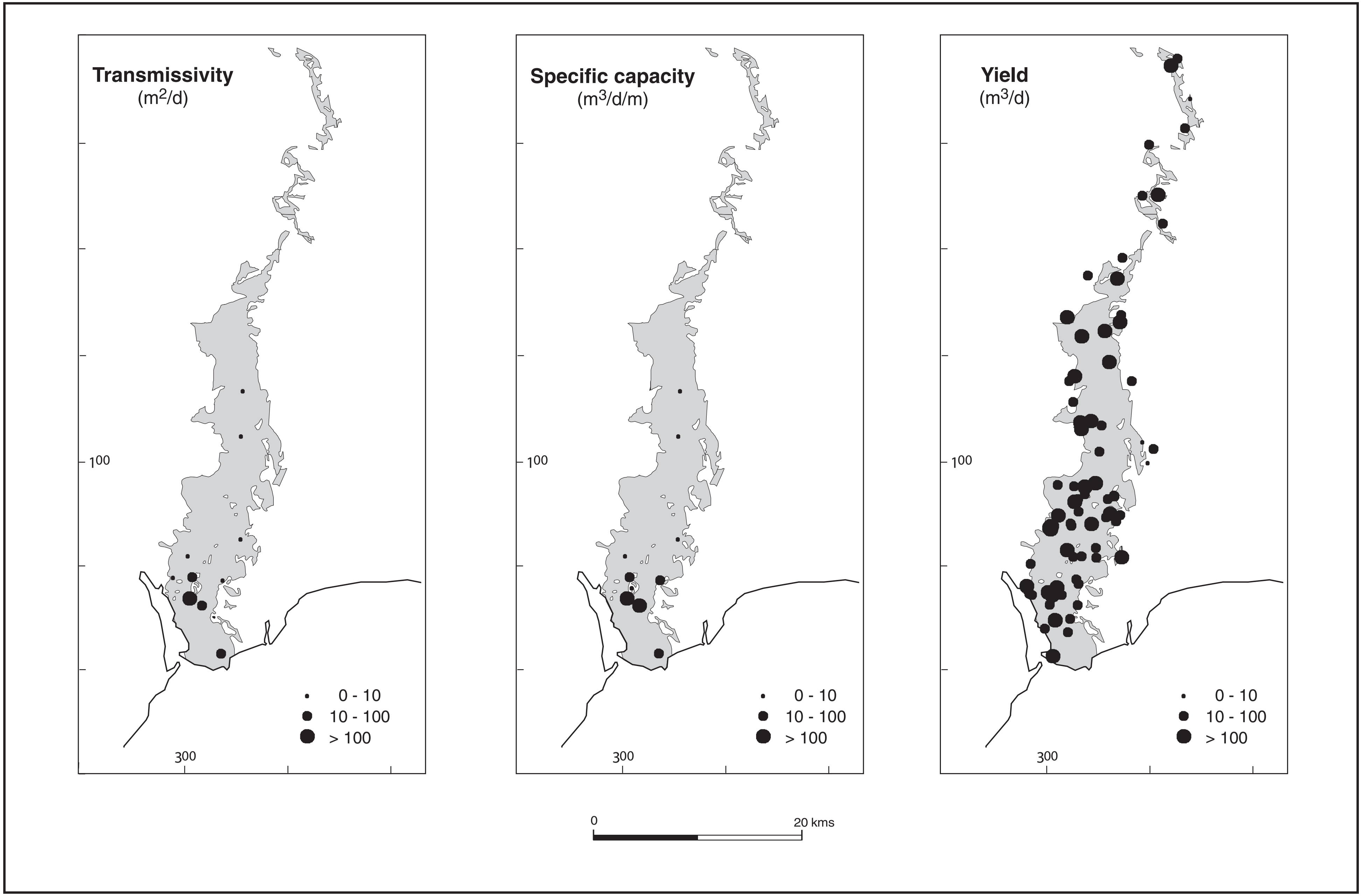

Figure 7.10 Transmissivity, specific capacity, and yield for the Aylesbeare Mudstone Group.

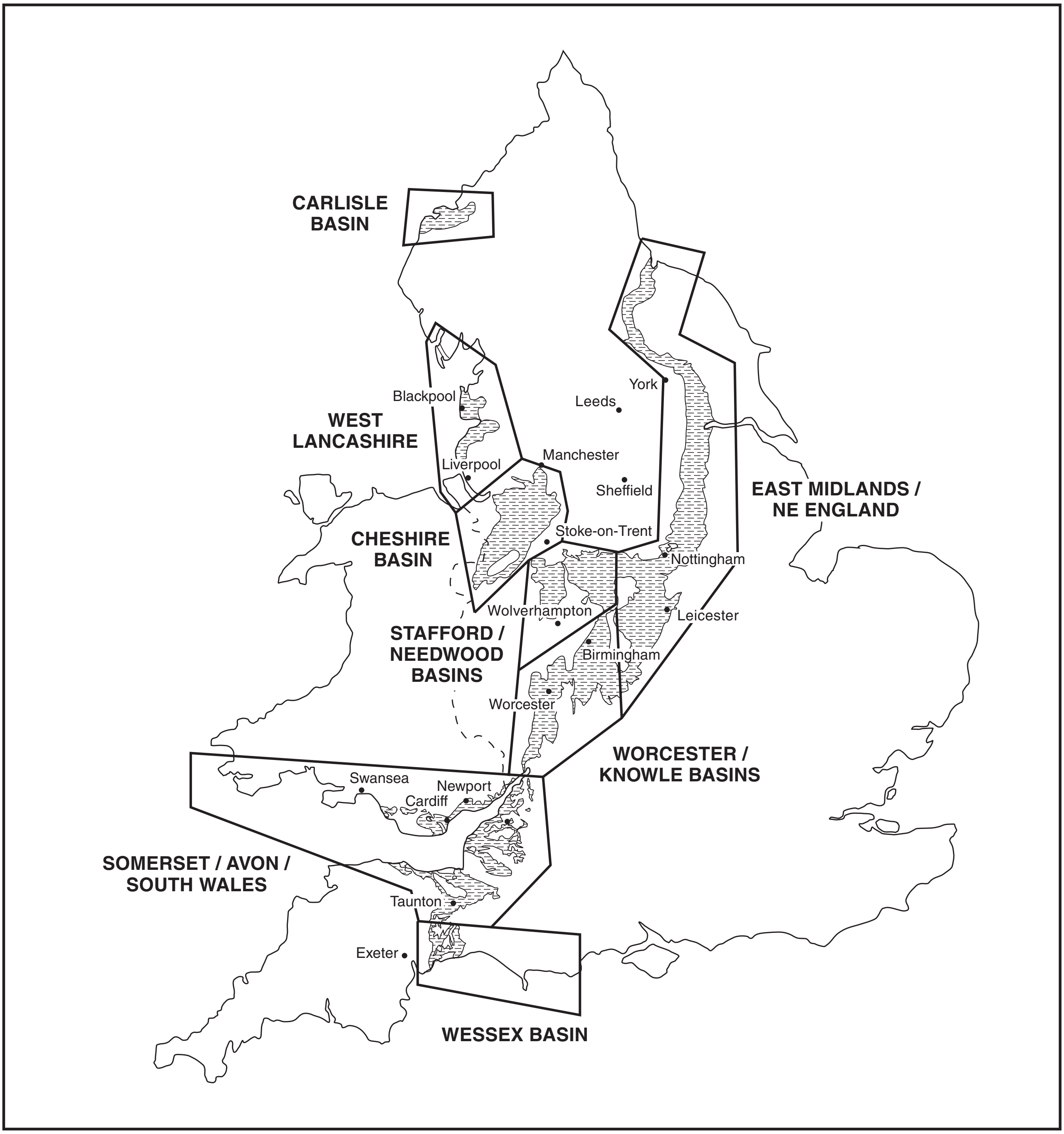

Figure 7.11 Mercia Mudstone Group, depositional basins.

continues northwards through Hereford and Worcester before broadening out to underlie much of the central Midlands. The outcrop then bifurcates around the Pennine Anticline, with the eastern limb running through Nottinghamshire into the Vale of York, before eventually reaching the North Sea coast at Teesside. The western limb underlies northern Shropshire, Cheshire and Merseyside and much of the Formby and Fylde peninsulas, passing offshore below the Irish Sea before extending onshore again on the northern side of the Lake District near Carlisle. In Cheshire, Warwickshire, the Vale of York and the Carlisle area, large parts of the outcrop are masked by thick Quaternary deposits (mainly glacial till), with more patchy cover of superficial deposits elsewhere. Thick sequences of the group dip and are concealed below younger Mesozoic rocks in Dorset, Hampshire, north-east England and the Southern North Sea. In south-east England, the group pinches out in the subsurface around the margins of the London Brabant Massif, an ancient cratonic area composed of Lower Palaeozoic rocks, such that it is absent at depth below London and the Home Counties.

The Mercia Mudstone Group is composed mainly of red and, less commonly, green and grey mudstones and siltstones. Substantial deposits of halite occur in the thicker, basinal successions of Somerset, Worcestershire, Staffordshire and Cheshire. Sulphate deposits (gypsum and anhydrite) and sandstone beds are common at some stratigraphical levels and are minor constituents throughout the remainder of the group. The Mercia Mudstone ranges in age from Early Triassic (late Scythian) to Late Triassic (Rhaetian). It generally overlies and confines the major, Early Triassic sandstone aquifer formed by the Sherwood Sandstone Group, but locally overlaps that group in extent to lie upon rocks of Carboniferous or older age. The Mercia Mudstone is itself overlain by the marine mudstones and thin limestones of the Penarth and Lias Groups.

The current lithostratigraphical classification of Triassic rocks in England and Wales is based on an extensive review carried out by the Geological Society of London and published in 1980 (Warrington et al., 1980). The terms Bunter and Keuper, based on supposed time correlation with the German Triassic sequence, were discontinued in favour of a more rigorous lithostratigraphical approach using the gross lithological characteristics of the various rock units. The former Bunter and Lower Keuper Sandstone units are now combined into the Sherwood Sandstone Group, with the Mercia Mudstone Group corresponding closely to the former Keuper Marl division.

A plethora of local names have been applied to formations within the Mercia Mudstone Group, reflecting either the original depositional restriction of units to individual basins or the geographical isolation of beds at outcrop due to post-Triassic erosion. With a few notable exceptions, formation names within the Mercia Mudstone are unique to individual basins (see Table 7.4). Despite this provincialism in nomenclature, five broad subdivisions are recognisable within the group in most basins and are used in the following description. Their relationship to the formal nomenclature is shown in Table 7.4.

Unit A

This is essentially a transitional lithological unit between the Sherwood Sandstone and Mercia Mudstone groups, and is characterised by interbedding of brown mudstone and siltstone with paler grey-brown sandstone in approximately equal proportions. Bedding is generally planar or sub-planar, and most sandstone beds are less than 0.5 m thick with intervening mudstone and siltstone partings of similar thickness. The sandstones are typically very fine to fine-grained, less commonly medium-grained, micaceous, and moderately cemented by ferroan calcite or dolomite. Intergranular porosities may be high. Beds of fine to medium-grained sandstone up to 5 m thick are present locally. These have a lenticular geometry with internal cross-stratification and probably represent sand-filled fluvial channels.

This unit was formerly known as the Keuper Waterstones and has been identified, though not necessarily named, in all the Triassic basins. South of Birmingham the unit tends not be recognised as a formation in its own right and is usually included in the top of the Sherwood Sandstone Group. Elsewhere, the unit forms the basal formation of the Mercia Mudstone Group and is assigned a different formational name (e.g. Tarporley Siltstone, Sneinton Formation, see Table 7.4) in each basin. The base of the unit is both conformable and gradational but also diachronous, becoming generally younger towards the south. The Eastern England Shelf is a notable exception; there the base of the unit is unconformable and is marked by a patchily distributed basal conglomerate up to 1 m thick with a strong calcareous cement.

The unit is typically a few tens of metres thick, though it reaches a maximum of 270 m in the Cheshire Basin.

Unit B

This unit consists mainly of red and, less commonly, green and grey dolomitic mudstones and siltstones. Sulphate deposits (gypsum and anhydrite) occur throughout the unit as veins. Thin beds of coarse siltstone and very fine sandstone occur at intervals throughout the unit. Individual sandstone beds are typically 2–6 cm thick, greenish grey in colour and have strong, dolomite cements. Less commonly, gypsum cements occur, these being dissolved by meteoric waters in the near surface to leave a weakly cemented or uncemented sand at outcrop. Sandstones are usually grouped into composite units of three or more beds, with greenish grey mudstone interbeds of equal thickness. These composite units vary from 0.15 to 1 m thick and many are sufficiently resistant to form low, cuesta-like landforms; these resistant beds are locally termed ‘skerries’, the more persistent of which have been named in some basins.

Substantial deposits of halite, some of considerable economic importance, occur within this unit in the thicker, basinal successions of Somerset, Worcestershire, Staffordshire, Cheshire and the Fylde (Table 7.4). The halite beds do not crop out at surface, but their projected surface position is often marked by subsidence hollows and collapse breccias formed in overlying strata. These features are not only formed by natural dissolution but also by the effects of brine pumping for salt extraction.

The unit is typically 150 to 300 m thick, though with substantial variation between basins. Up to 1200 m occurs in the Cheshire Basin, which includes two thick halite units with an aggregate thickness of over 600 m.

Unit C

This is a thin but widespread unit which can be traced from the Dorset coast into Nottinghamshire. The unit has not been recognised in Staffordshire and basins to the north-west. In central England, between Worcestershire and Warwickshire, the unit is represented by the Arden Sandstone. Equivalents in south-west England are named as the Butcombe, North Curry and Weston Mouth sandstones. The Dane Hills Sandstone of Leicestershire and the Hollygate Sandstone of the Nottingham district represent this unit in the East Midlands.

In central and south-west England the unit typically consists of up to 12 m of thickly bedded, medium to coarse-grained cross-stratified sandstone. The sandstone is moderately to strongly calcareous or dolomitic, the most resistant beds having been quarried locally for building stone. These beds of sandstone are, however, discontinuous and lenticular in geometry and probably represent the fills of fluvial channels. Thick sandstones are absent in many places, where the unit is represented solely by dark greenish grey siltstones and mudstones with a few thin beds of dolomitic, very fine to fine-grained sandstone. In the East Midlands, the Hollygate Sandstone consists of up to 8 m of fine to medium-grained pale grey sandstone interbedded with predominantly red-brown mudstone; the sandstone beds are cemented mainly by gypsum with stronger cementation by intergranular dolomite or quartz overgrowths occurring in small patches and thin beds only. The sandstones thus weather to a very poorly cemented or uncemented sand in the near surface, though are more competent at depths in excess of a few metres.

Unit D

This unit resembles Unit B, but the resistant dolomitic sandstone units (‘skerries’) are less common and structureless red-brown, dolomitic mudstones dominate. Halite is absent but beds, nodules and veins of gypsum are abundant; locally, they form deposits of economic importance, for example near Burton-on-Trent, Nottingham and Newark.

Table 7.4 Correlation of the Mercia Mudstone Group across depositional basins.

WESSEX BASIN	SOMERSET/ AVON/ SOUTH WALES	WORCESTER/ KNOWLE BASINS	STAFFORD/ NEEDWOOD BASINS	CHESHIRE BASIN	WEST LANCASHIRE	CARLISLE BASIN	EAST MIDLANDS/ NE ENGLAND	*MERCIA MUDSTONE GROUP UNIT*
PENARTH GROUP						PENARTH GROUP		
Blue Anchor Formation (24m)	Blue Anchor Formation (30 - 40m)	Blue Anchor Formation (7 - 11m)	Blue Anchor Formation (7 - 18m)	Blue Anchor Formation (15m)	absent	Stanwix Shales (up to 300m)	Blue Anchor Formation (4 - 10m)	**E**
mudstone (up to 125m)	mudstone (up to 130m)	Twyning Mudstone Formation (60 - 125m)	mudstone (up to 135m)	Brooks Mill Mudstone Formation (160m)			Cropwell Bishop Formation (30 - 80m)	**D**
Weston Mouth Sandstone (11m)	Butcombe /North Curry Sandstone (up to 7m)	Arden Sandstone (3 - 12m)					Dane Hills/ Hollygate Sandst (up to 10m)	**C**
mudstone (up to 175m)	Somerset Halite (up to 150m)	Droitwich Halite (up to 45m)	Stafford Halite (up to 65m)	Wilkesley Halite (up to 400m)	Breckells and Kirkham Mudstone formations (up to 450m)		Edwalton, Gunthorpe and Radcliffe formations (up to 160m)	**B**
	mudstone (thickness unknown)	Eldersfield Mudstone Formation (up to 350m)	mudstone (up to 180m)	Wych and Byley Mudstone formations (up to 580m)				
				Northwich Halite (up to 290m)	Preesall Halite (up to 200m)			
				Bollin Mudstone formations (up to 460m)	Singleton and Hambleton Mudstone formations (up to 180m)			
SHERWOOD SANDSTONE GROUP	SHERWOOD SANDSTONE GROUP	Sugarbrook Member (10 - 45m)	Maer/Denstone Formation (up to 160m)	Tarporley Siltstone Formation (up to 270m)			Sneinton Formation (up to 90m)	**A**
		SHERWOOD SANDSTONE GROUP	SHERWOOD SANDSTONE GROUP	SHERWOOD SANDSTONE GROUP	SHERWOOD SANDSTONE GROUP	SHERWOOD SANDSTONE GROUP	SHERWOOD SANDSTONE GROUP	

Gypsum is absent in the near surface due to dissolution by meteoric water, weakening the fabric of the rock and locally resulting in a lowering of the land surface by up to 2 to 3 m.

The unit is represented by the Twyning Mudstone in the Worcester Basin, the Brooks Mill Mudstone in the Cheshire Basin and the Cropwell Bishop Formation in the East Midlands. The unit is unnamed elsewhere. As with Unit B, the unit thickens substantially into the depositional basins, with the thickest sequences (140–160 m) developed in the Cheshire Basin and the thinnest (30 m) in the East Midlands.

Unit E

This thin but widespread unit is the uppermost within the Mercia Mudstone Group and is represented in all basins except the west Lancashire area. A single name, the Blue Anchor Formation, has been applied to the unit. In south-west England and South Wales, it consists of interbedded greenish-grey, dark grey and green dolomitic mudstones and dolostones with common gypsum. Elsewhere, the unit is more homogeneous in lithology, consisting of the apparently structureless, pale greenish grey dolomitic mudstones and siltstones known formerly as the Tea Green Marl.

The unit is up to 40 m thick in south-west England but is generally less than 15 m thick elsewhere. It was probably deposited in a coastal sabkha environment with periodic marine influence, preceding the widespread marine transgression that deposited the dark grey to black mudstones of the lower part of the overlying Penarth Group (Westbury Formation). The base of the overlying Penarth Group is a non-sequence, typically resting on a shrinkage-cracked and bored top surface of the Blue Anchor Formation.

Marginal conglomerates

Towards the margins of depositional basins and on the flanks of contemporaneous landmasses such as the Mendips and Charnwood Forest, the Mercia Mudstone Group contains abundant, though laterally impersistent, beds of conglomerate and breccia, commonly cemented strongly by dolomite. These conglomerates were originally deposited as alluvial fanglomerates and contain abundant large, often angular pebbles of local derivation. They are especially common towards the base of the group where it onlaps onto Carboniferous or older rocks. The Dolomitic Conglomerate Formation on the flanks of the Mendips is one well-known example. Sandstone beds also occur locally towards basin margins in some other areas; the Redcliffe Sandstone of the Bristol area, which is up to 50 m thick, is a notable example.

7.3.2.2 *Depositional history*

During Permian and Triassic times, England and Wales lay much closer to the equator in the subtropical interior of the supercontinent of Pangaea, which assembled following continental collision in the late Carboniferous period. By the Early Permian, Pangaea was already showing the first signs of breaking apart. Tensional stresses within the crust led to the formation of a series of small, fault-bounded, subsiding basins in southern, central and north-west England. Eastern England lay on the margin of a much larger subsidence, the Southern North Sea Basin, which covered much of north-west Europe. These basins continued to influence deposition throughout the Permian and Triassic periods. In the Early Triassic, monsoonal rains fed a major, northwards-flowing river system which deposited thick sequences of pebbly sands, now preserved as the Sherwood Sandstone Group. Lower formations within the Sherwood Sandstone were restricted to the basins, but upper formations began to overlap onto the adjacent higher relief. In the Mid Triassic, climatic conditions became progressively more arid, and inland sabkhas with saline mudflats and temporary lakes replaced the fluvial environments of the Sherwood Sandstone Group.

The Mercia Mudstone Group was deposited in these mudflat environments in three main ways; settling-out of mud and silt in temporary lakes, rapid deposition of sheets of silt and fine sand by flash floods, and accumulation of windblown dust on the wet mudflat surface. The change from fluvial to inland sabkha environments was not synchronous throughout England and Wales, with fluvial deposition persisting in the south while the sabkhas advanced from the north. The base of the Mercia Mudstone Group is thus diachronous, with the lowest beds of the group becoming progressively younger southwards. The thickest Mercia Mudstone sequences continued to accumulate within fault-bounded basins, but as deposition gradually transgressed onto the Carboniferous and older rocks of adjacent highs, so the group began to overlap beyond the underlying Sherwood Sandstone in geographical extent. The terrestrial deposition conditions of the group were finally terminated in Late Triassic times when rising sea level flooded the mudflats and laid down the widespread, dark grey to black marine mudstones of the lower part of the Penarth Group.

7.3.2.3 *Structural geology*

In most parts of England and Wales the Mercia Mudstone has been subjected to only mild tectonic deformation. Dips are generally less than five degrees except in the near vicinity of faults, though steeper radial dips occur locally around the flanks of contemporaneous landmasses such as the Mendips. Larger faults affecting the Mercia Mudstone, for example in the Cheshire Basin, represent reactivations of earlier, Carboniferous or older structures. Recent geological mapping of the Mercia Mudstone in the Nottingham and Worcester districts indicates that the group is disturbed by numerous small faults; these may be present elsewhere but are not mappable below even a thin cover of superficial deposits. Though most of these faults have throws of 5 m or less, this is often sufficient to isolate blocks of minor aquifers formed by the thin beds of dolomitic siltstone and sandstone within the Mercia Mudstone succession. Locally, bed collapse structures can also occur as a result of solution/removal of underlying halite deposits.

7.3.3 Hydrogeology

7.3.3.1 *Introduction*

The groundwater-bearing characteristics of the Mercia Mudstone Group derive from the interbedding of effectively impermeable mudstones interbedded with occasional thin impersistent siltstones and sandstones (skerries). Despite being generally thin (often less than 1 m thick) and very well cemented, the sandstone and siltstone horizons may contain and transmit limited quantities of groundwater through fractures. Skerries are present, to a varying degree, throughout most of the mudstone sequence except the uppermost Blue Anchor Formation (Unit E). They attain greatest thickness, (sometimes in excess of 10 m in the case of the Arden Sandstones), and are laterally most persistent in Unit C. Thicker sandstone horizons are also more common in the basal part of the sequence (Unit A), where the groundwater is sometimes in hydraulic continuity with the underlying Sherwood Sandstone aquifer. Yields obtainable from skerries commonly range from less than 25 m^3/d to 130 m^3/d for very variable amounts of drawdown. The lateral impersistance of the skerries in the Midlands results in rather smaller yields, which often decline with time as pumping depletes storage within the water-bearing horizons.

As a result of this, yields from a partially saturated sandstone horizon may initially be acceptable but are likely to decline as the water table falls due to storage depletion. A study of borehole yields throughout the Midlands indicated a 50% probability of obtaining a yield in excess of about 70 m^3/d for a drawdown of less than 10 m from a 150 mm diameter borehole and a 75% probability of a yield in excess of 17.5 m^3/d (Monkhouse, 1984). Although of greater thickness, the Arden Sandstone commonly also provides yields of this order throughout the Knowle Basin (Powell et al., in press).

Boreholes generally stand without support except in the Midlands and sand screens are only rarely installed. Elsewhere it is only necessary to line the uppermost 10 to 15 m with plain casing to support weathered mudstones and prevent contamination from surface waters (Old et al., 1991).

Regionally, in the East Midlands, west of the Pennines, in the centre and north of the Cheshire basin, and in north-west England, few boreholes successfully abstract water from the group. Boreholes in these areas are often dry or encounter saline or brackish water due to the dissolution of the halite deposits, present as beds or cement within the mudstones, which are relatively common in these areas (Wilson and Evans, 1990).

7.3.3.2 *Groundwater flow and recharge*

As previously described, yields frequently decline with time as pumping depletes storage within the water-bearing horizons. Figure 7.12 illustrates diagrammatically various other features typical of the flow regimes of the Mercia Mudstones aquifer:

(i) The thin skerries commonly possess a very small out crop area and recharge is therefore limited.

(ii) Some skerries are laterally impersistent and are totally enclosed within the mudstones. Under such circumstances recharge is limited to that which moves slowly through the mudstones; storage is therefore likely to be rapidly depleted on pumping and yields will decline dramatically with time.

(iii) Failure to penetrate a skerry or one which is only poorly fractured (not an uncommon event), results in a dry or very low yielding borehole.

(iv) Thicker sandstone horizons, such as the Arden Sandstones, are often located on higher ground and although their larger outcrop permits greater recharge their elevated position can result in rapid drainage with springs issuing at their lower margin.

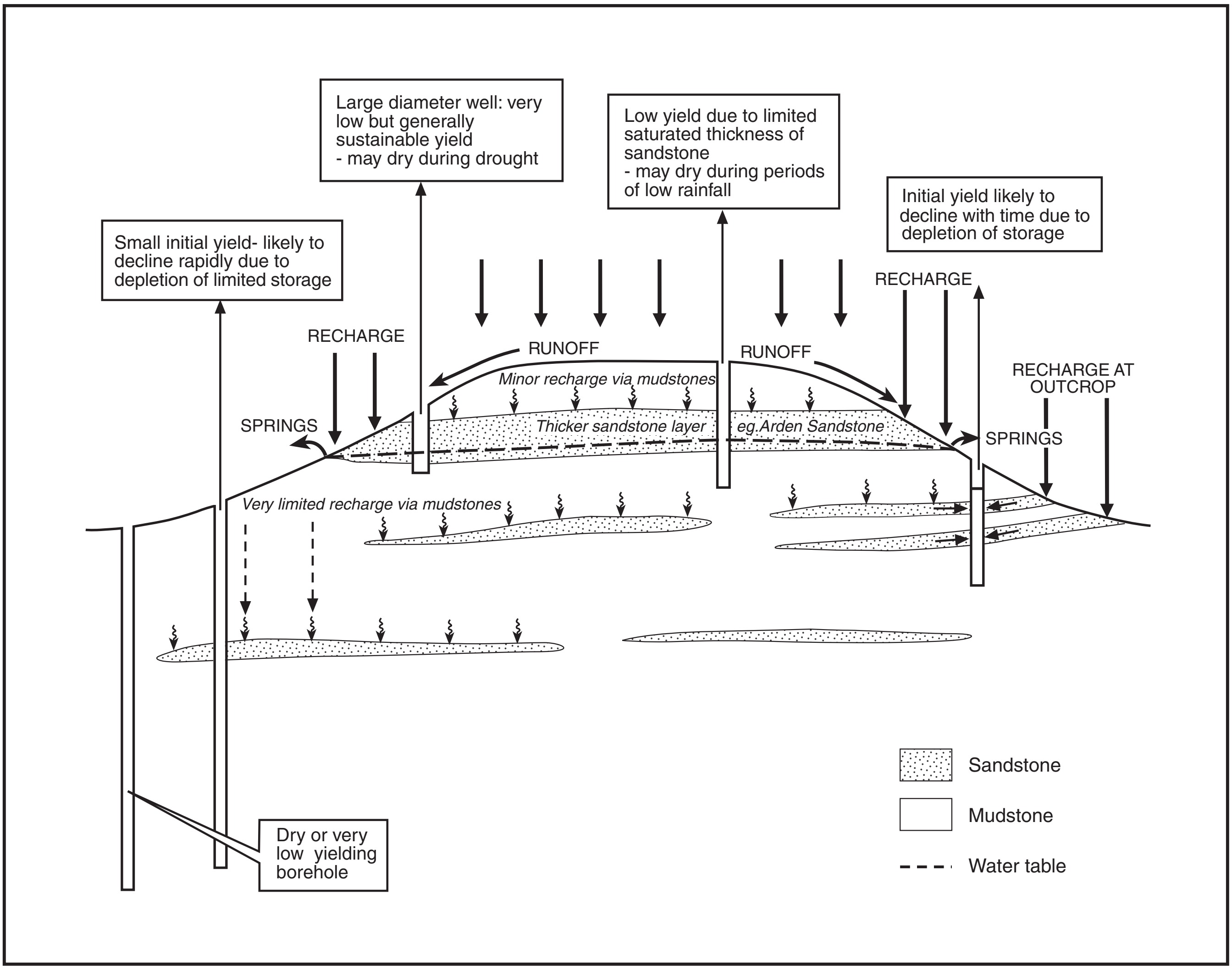

Figure 7.12 Flow regimes of the Mercia Mudstone aquifer.

Since the skerries are thin, commonly only few metres or less, they contribute to a small proportion of the nominal saturated depth of boreholes and wells; however, they confer a very large proportion of the yield, with the mudstones contributing little or nothing. Rarely supplies have been obtained from cavernous horizons associated with the partial dissolution of gypsum beds, for example in the Thirsk area (Powell et al., 1992). Groundwater contained within the skerries is generally confined by the overlying mudstones.

7.3.3.3 *Effects of overlying/underlying deposits*

Downing et al. (1970) report that where the Mercia Mudstone Group is overlain by permeable superficial deposits like alluvial or glacial sands and gravel, as in the Trent valley, a significant proportion of the yield of a borehole/well may be derived from these deposits rather than from the underlying marls. Although this is a reasonable theory, it was not possible to substantiate this observation from available records.

In the vicinity of the Mendips the conglomerates of the marginal facies commonly overlie the Carboniferous Limestone or less commonly Devonian Old Red Sandstone, with both of which they are considered to be in hydraulic continuity. This hydraulic continuity was considered to explain the high yield of almost 328 m^3/d, obtained from a 200 mm diameter borehole located to the east of Weston-super-Mare [ST 3615 6281] and at least two other similar successful boreholes in the district (Whittaker and Green, 1983). Differences in head between the aquifers can be in either direction with the result that in some areas, Triassic groundwater is lost rapidly to the underlying Carboniferous Limestones. Green and Welch (1965) reported that in the North Hill area of the Mendips, where the Triassic is underlain by the Old Red Sandstone, 17th century mining operations encountered considerable difficulty due to the presence of groundwater in the Dolomitic Conglomerate. Artesian flow due to confinement by overlying mudstones is often encountered.

7.3.3.4 *Core data*

Porosity and permeability data are available for 34 outcrop samples from six locations and for seven sample depths from only a single deep geothermal borehole (located at Western Esplanade, Southampton, [SU 41560 12020]).

Porosity values obtained from outcrop samples ranged from 12 to 31% (average 25%) whilst permeabilities ranged between 0.0096 and 2.35 m/d (average 0.56 m/d). The lowest values were obtained from a railway cutting site located near Runcorn Cheshire [SJ 51010 82380] with an average porosity of 20% and permeability of 0.017 m/d. Statistical analysis of this dataset would prove misleading with higher values than are considered to be the actual case in the saturated aquifer, as all of the samples are likely to have been of weathered sandstone horizons (skerries). The lower values from the railway cutting sample are more likely to representative, being less weathered in a recent man-made exposure.

The samples obtained from the borehole were mainly of fine grained sandstones at depths of between 1708 to 1729 m below surface. Porosity values ranged from 6.4 to 12.5% (average 9.3%) and hydraulic conductivities from 0.000006 to 0.00017 m/d (average 0.000096 m/d). The latter are very low permeabilities. As they were obtained from depths where the sandstones are unlikely to have been subject to weathering, they tend to support the field observation that groundwater flow from the sandstone skerries derives from the fractures and not from the matrix.

Although no mudstone samples have been tested, they may be regarded as effectively impermeable, with a hydraulic conductivity of the order of 0.01 m/d (Black and Barker, 1981).

7.3.3.5 *Pumping test data*

Data distribution

For the purpose of statistical analyses, aquifer properties data have been grouped into three main geographical areas as described below.

A moderately high density of test results is available on the Aquifer Properties Database over the outcrop area of the Wessex Basin and the Somerset/Avon area to the north (Figure 7.13). The only data available for south Wales is located at the western extremity of the outcrop to the north of Porthcawl, with unfortunately no results available for the Cardiff area where higher yields have commonly been obtained from the marginal conglomerate at the base of the group. These areas have been grouped together as the 'south-west'.

Numerous results are available for sites located in the Worcester/Knowle Basins and in the East Midlands (in the Nuneaton/Leicester/Loughborough area) but further to the north and in the Stafford/Needlewood Basin (Figure 7.13) the data are rather fewer. Sites in these areas have been grouped together and referred to as 'the Midlands'.

A distinct cluster of 43 sites is found on the southern margins of the Cheshire Basin (in the general vicinity of Whitchurch).

In northern England test results are distinctly sparse and although a few sites located in the north-west are allocated to the Mercia Mudstone Group, on closer examination it is often unclear if boreholes tap only the group, if they also penetrate the underlying Sherwood Sandstone, or if they receive some contribution from overlying superficial deposits. North of Nottingham, the few sites for which results are available are widely scattered along the outcrop. The distribution of sites in northern England is considered to be too sparse to merit analysis as a distinctive grouping, and is therefore only included in the statistics for the Mercia Mudstone Group as a whole.

It should however be noted that the data set is inherently biased since higher yielding boreholes are more likely to have been test pumped than those with lower yields and thus lower production potential. This introduces a bias towards higher values in the database. In addition dry (or effectively dry) boreholes, which undoubtedly exist, are entirely absent from the database, giving a false impression of both the magnitude of yield typically obtainable and the success rate of boreholes drilled into the Mercia Mudstone Group.

Test results

A summary of pumping-test derived aquifer properties data for Mercia Mudstone Group sites is shown in Table 7.5 both for the group as a whole and divided by geographic areas (south-west, Midlands and south Cheshire Basin).

The geographical distribution of transmissivity and specific capacity is shown in Figure 7.13. Distribution histograms and cumulative frequency plots of specific capacity, transmissivity and storage coefficient for the whole of the Mercia Mudstone Group data set are shown in Figures 7.14, 7.15 and 7.16, and for the south-west area in Figures 7.17, 7.18 and 7.19. Figures 7.20 and 7.21 show distribution histograms and cumulative frequency plots of specific capacity and transmissivity for the Midlands area, and Figure 7.22 is a similar plot for the specific capacity data for the South Cheshire Basin area.

Table 7.5 Summary of aquifer properties data for the Mercia Mudstone Group.

All Mercia Mudstone Group		
Total number of records	149	—
Number of transmissivity records	149	—
Minimum/maximum transmissivity value	0.75	5167
Arithmetic/geometric mean of transmissivity (m^2/d)	126	18.6
Median/interquartile range of transmissivity (m^2/d)	17.5	70.4
25/75 percentile of transmissivity (m^2/d)	4.59	75.0
Number of storage coefficient records	17	—
Minimum/maximum storage coefficient value	.000095	0.99
Number of specific capacity records	140	—
Minimum/maximum specific capacity (m^3/d/m)	0.6	1800
Arithmetic/geometric mean of specific capacity (m^3/d/m)	53.8	12.3
Median/interquartile range of specific capacity (m^3/d/m)	12.5	35.1
25/75 percentile of specific capacity (m^3/d/m)	3.64	38.7
South-west		
Total number of records	37	—
Number of transmissivity records	29	—
Minimum/maximum transmissivity value (m^2/d)	1.0	5167
Arithmetic/geometric mean of transmissivity (m^2/d)	240	30.0
Median/interquartile range of transmissivity (m^2/d)	22.0	135.7
25/75 percentile of transmissivity (m^2/d)	9.40	145.1
Number of storage coefficient records	13	—
Minimum/maximum storage coefficient value	0.01	0.99
Number of specific capacity records	36	—
Minimum/maximum specific capacity (m^3/d/m)	1.36	1800
Arithmetic/geometric mean of specific capacity (m^3/d/m)	141	43.2
Median/interquartile range of specific capacity (m^3/d/m)	41.9	76.1
25/75 percentile of specific capacity (m^3/d/m)	16.3	92.5
Midlands		
Total number of records	59	—
Number of transmissivity records	39	—
Minimum/maximum transmissivity value (m^2/d)	0.75	402
Arithmetic/geometric mean of transmissivity (m^2/d)	46.8	12.3
Median/interquartile range of transmissivity (m^2/d)	12.2	60.1
25/75 percentile of transmissivity (m^2/d)	2.50	62.6
Number of storage coefficient records	2	—
Number of specific capacity records	59	—
Minimum/maximum specific capacity (m^3/d/m)	0.68	320
Arithmetic/geometric mean of specific capacity (m^3/d/m)	24.7	9.4
Median/interquartile range of specific capacity (m^3/d/m)	8.3	16.2
25/75 percentile of specific capacity (m^3/d/m)	2.95	19.2
South Cheshire Basin		
Total number of records	43	—
Number of transmissivity records	7	—
Minimum/maximum transmissivity value (m^2/d)	1.0	175
Arithmetic/geometric mean of transmissivity (m^2/d)	74.9	23.6
Median/interquartile range of transmissivity (m^2/d)	51.5	166
25/75 percentile of transmissivity (m^2/d)	—	—
Number of storage coefficient records	2	—
Number of specific capacity records	40	—
Minimum/maximum specific capacity (m^3/d/m)	0.6	364
Arithmetic/geometric mean of specific capacity (m^3/d/m)	21.6	6.1
Median/interquartile range of specific capacity (m^3/d/m)	6.02	15.3
25/75 percentile of specific capacity (m^3/d/m)	1.92	17.2

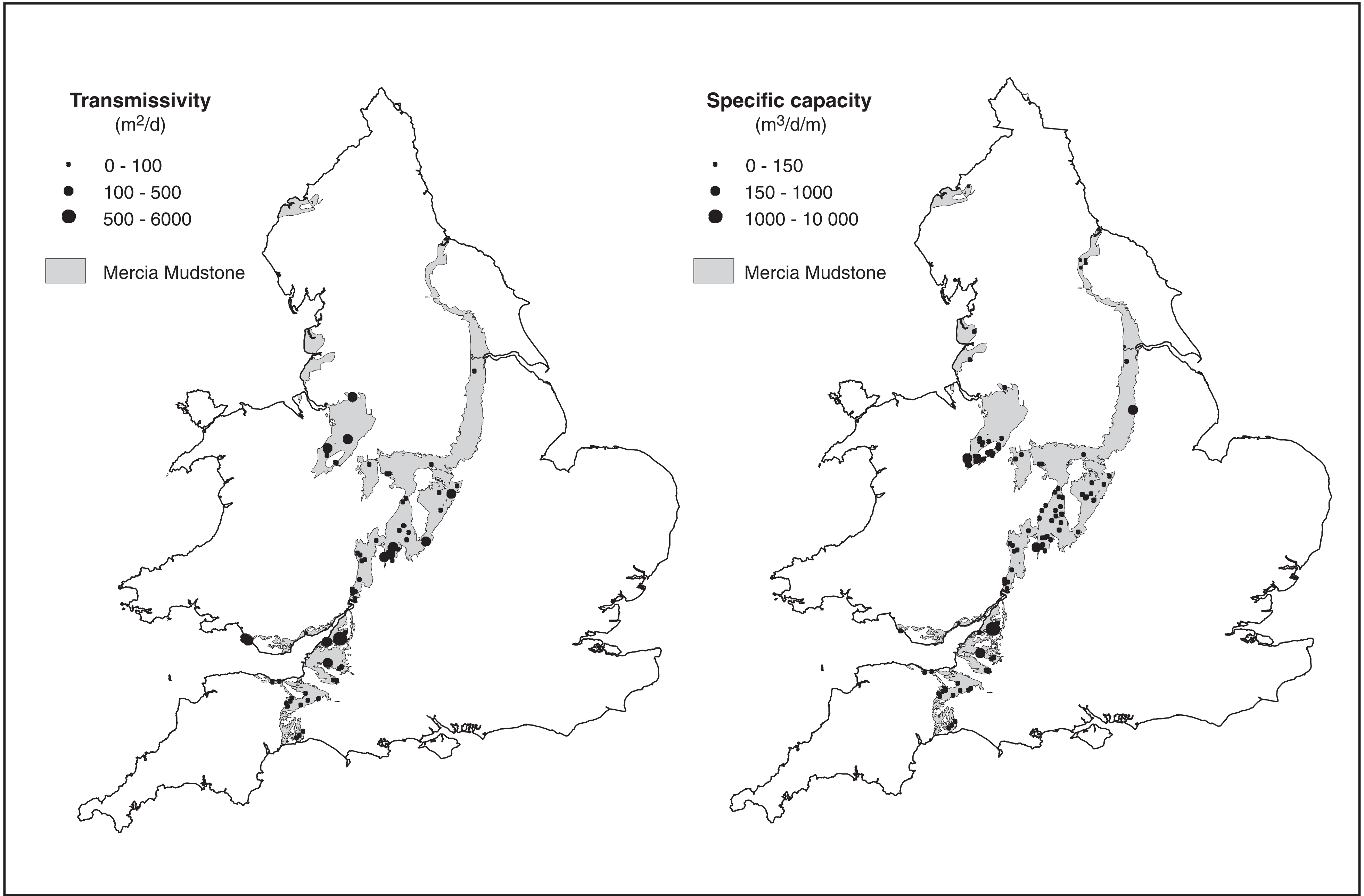

Figure 7.13 Transmissivity and specific capacity, Mercia Mudstone Group.

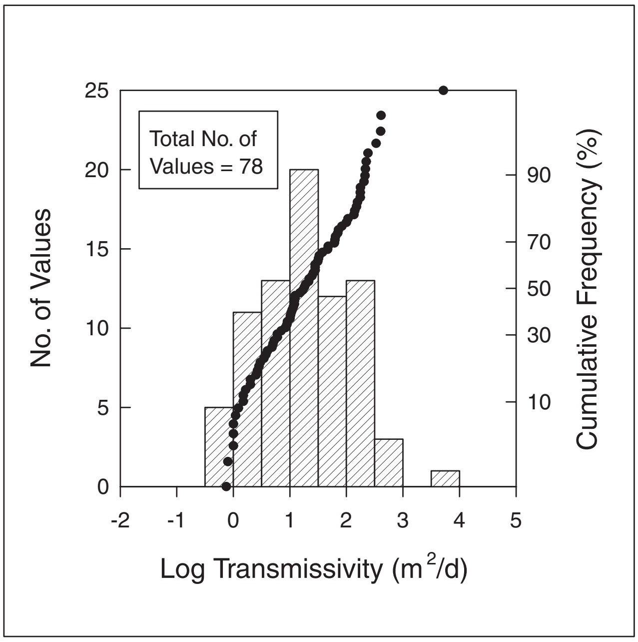

Figure 7.14 Distribution of all transmissivity values for the Mercia Mudstone Group.

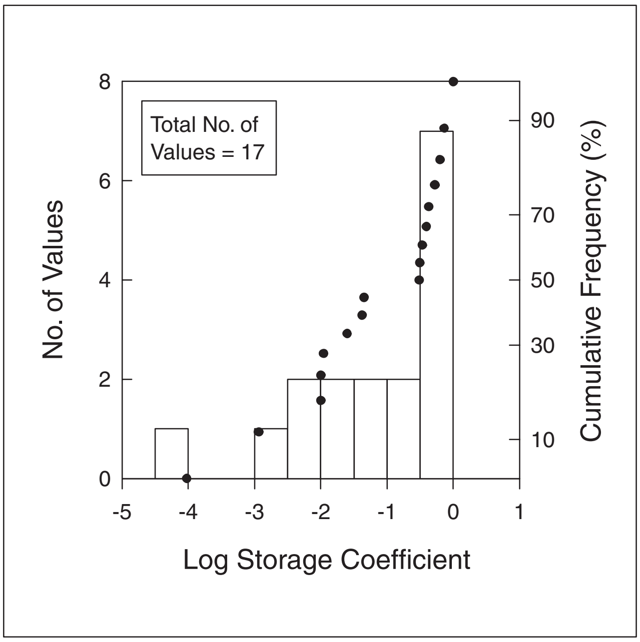

Figure 7.16 Distribution of all storage coefficient values for the Mercia Mudstone Group.

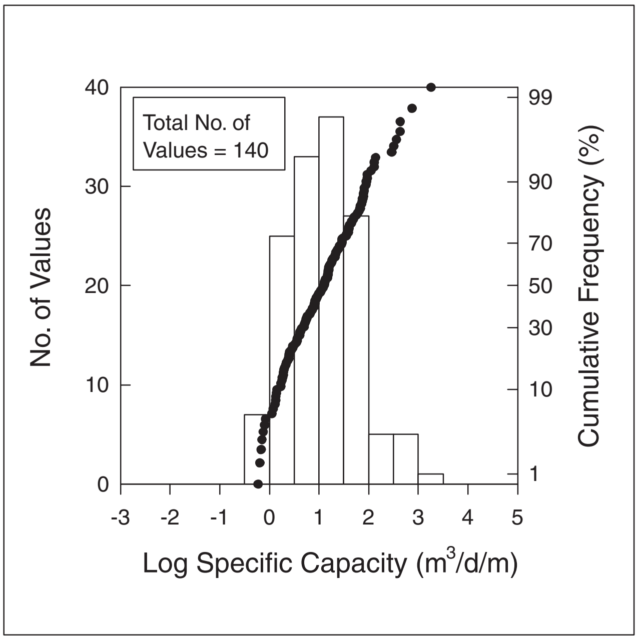

Figure 7.15 Distribution of all specific capacity values for the Mercia Mudstone Group.

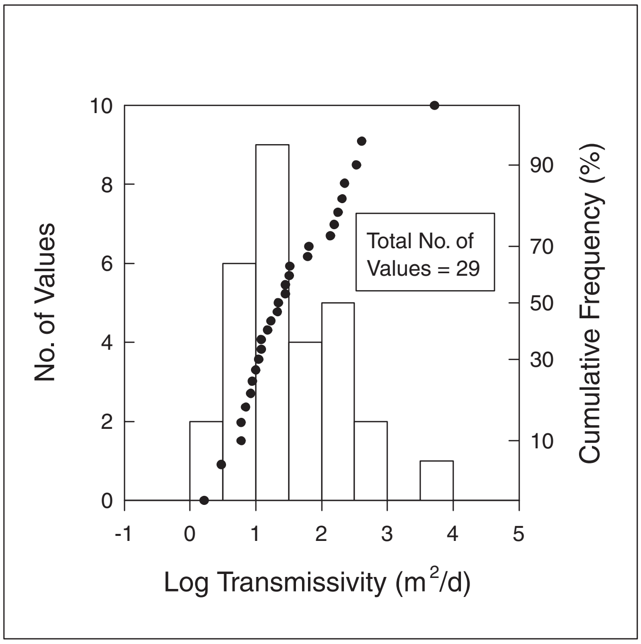

Figure 7.17 Distribution of transmissivity values for the Mercia Mudstone Group; south-west.

Transmissivity

Geographically, transmissivity values are greatest in the south-west with a range of 1 to 5167 m^2/d, and geometric mean of 30 m^2/d. Values for the Midlands and the South Cheshire Basin show a smaller range, although the geometric means are not dissimilar (12.3 m^2/d and 23.6 m^2/d respectively) (Table 7.5). Many of the highest values in the south-west, in the south Wales and Bristol/Mendips area are located close to the margins of Carboniferous Limestone outcrops. Such high transmissivities in the group's basal marginal facies may be due in part to karstic development and in part to the existence of hydraulic continuity with the underlying Carboniferous Limestone aquifer. Geological logs available on the database are however insufficiently detailed to demonstrate that this is indubitably the case.

Specific capacity

Although specific capacity values are available for virtually all sites contained in the database, the values should be treated with much caution. As indicated above, virtually all of the yield of most boreholes penetrating the Mercia Mudstone Group is contributed from thin skerry horizons with little or no contribution from the dominant mudstone lithologies. It is only rarely possible to determine the precise

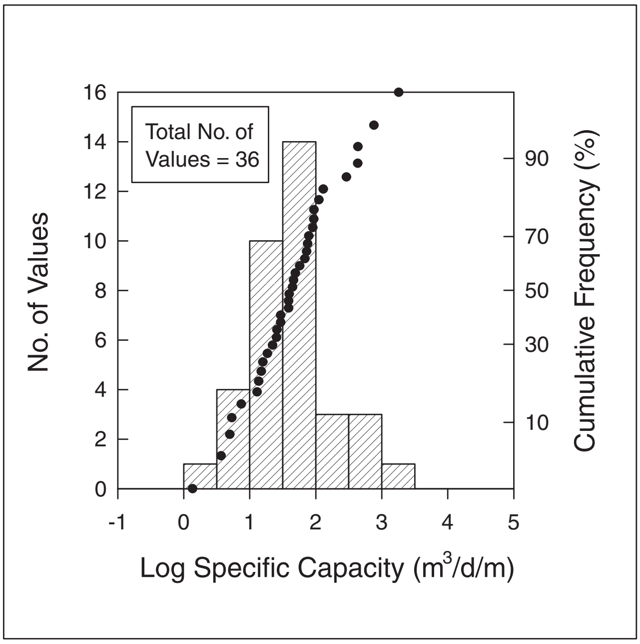

Figure 7.18 Distribution of specific capacity values for the Mercia Mudstone Group; south-west.

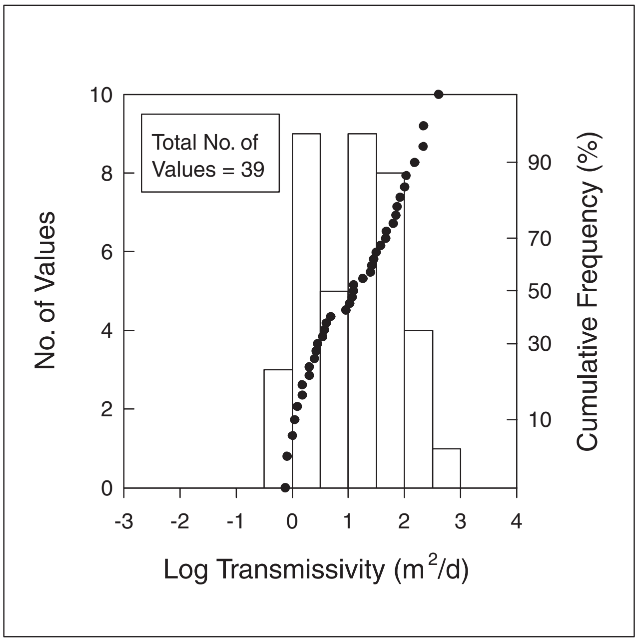

Figure 7.20 Distribution of transmissivity values for the Mercia Mudstone Group; Midlands.

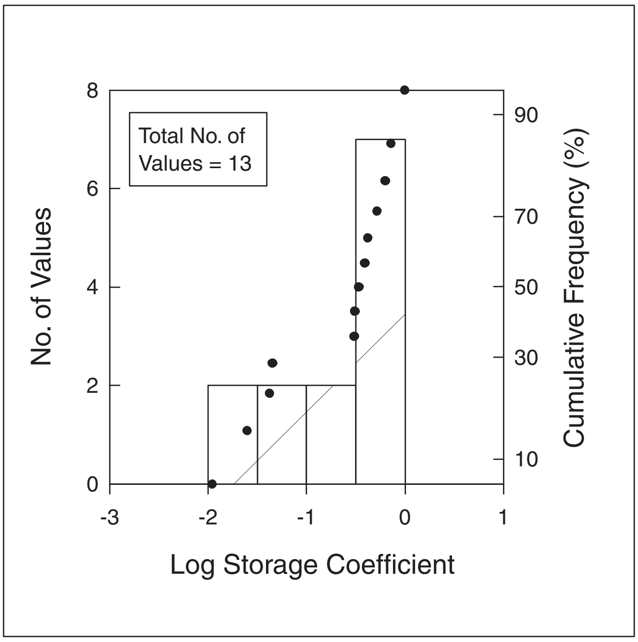

Figure 7.19 Distribution of storage coefficient values for the Mercia Mudstone Group; south-west.

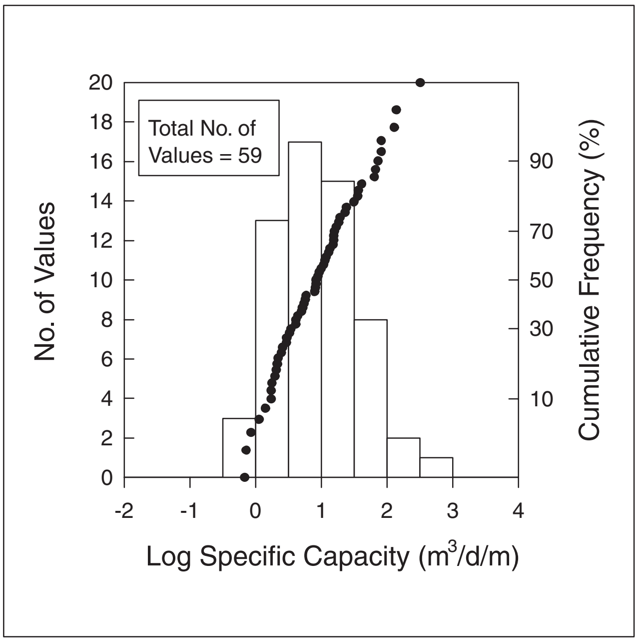

Figure 7.21 Distribution of specific capacity values for the Mercia Mudstone Group; Midlands.

thickness of the contributing sandstones, (some of which may in any case be effectively dry due to a lack of fractures), from available drillers geological logs. In consequence the assumption that the whole saturated thickness of strata penetrated contributes to the yield is not valid, and in many cases, the contributing horizons may only be a metre or two of sandstone thickness.

Although minimum specific capacity values are very similar in all geographic areas, the highest values are associated with sites located in the south-west (Table 7.5). The geometric mean and interquartile range are also significantly higher than for other areas. This is due to the localised presence of marginal conglomerates at the base of the group which commonly produce high yields for relatively small amounts of drawdown. Although only locally developed and laterally impersistent, they have traditionally been targeted for production wells. Values for the Midlands and South Cheshire Basin areas are rather lower and remarkably consistent, and are possibly indicative of very similar aquifer conditions in the two areas. In both areas the higher specific capacity for site values are located predominantly near the lower boundary outcrop margins suggesting that the boreholes are likely to have penetrated the more arenaceous basal Tarporley/Sneinton formations. The data approach a normal distribution both for the whole group and individual areas.

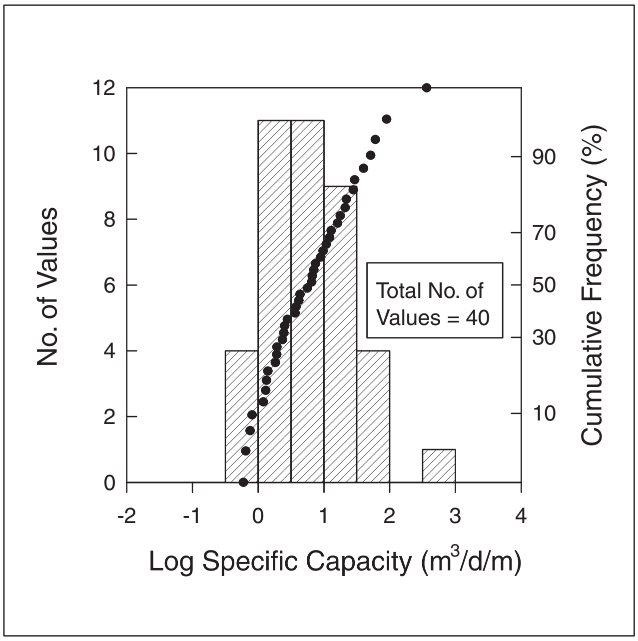

Figure 7.22 Distribution of specific capacity values for the Mercia Mudstone Group; Cheshire.

Storage coefficients

The two storage coefficients for the Midlands are indicative of highly confined conditions, whilst the two for the South Cheshire Basin area are unconfined values. Surprisingly all 13 values available for the south-west are very high and indicative of unconfined conditions, although many of the values are in fact so high as to be considered unrealistic. Complex hydraulic conditions in the marginal facies militate against a simplistic interpretation of these high storage coefficients, except insofar as they imply ready and rapid recharge/leakage which would simulate the unconfined drainage response. This is consistent with an aquifer setting known to be karstic and thought in some hydraulic situations to be receiving upward leakage from the Carboniferous Limestone and/or downward leakage from overlying transitional arenaceous facies like the Redcliffe Sandstone.

There are no values indicative of the confined conditions which would commonly be expected, given the hydrogeological characteristics of Mercia Mudstone Group away from the marginal facies. As a result, even those values of the order of 1×10^{-2} must be viewed with extreme caution.

7.3.3.6 *Yield data*

Yields much in excess of the normal range are relatively rare and are often given particular mention in geological memoirs; for example almost 260 m^3/d from a borehole penetrating the Cropwell Bishop Formation (Unit D) at Aston Garden Centre [SK 4133 3096] in the Loughborough area (Lewis, 1998), almost 380 m^3/d in the Worcester area (Barclay et al., 1997) and almost 200 m^3/d from a borehole at Ashborne Hill near Banbury (Edmonds et al., 1965). A number of higher yielding boreholes were also drilled in the Stratford-upon-Avon and Evesham area (Williams and Whittaker, 1974), with yields of 1089 m^3/d and almost 545 m^3/d obtained from a pair of 356 mm diameter boreholes at Dunnington Heath Farm [SP 066 539], 406 m^3/d from a 254 mm diameter borehole at Rushford Farm [SP 0585 5155] and almost 328 m^3/d from a 203 mm diameter borehole at Salford Priors [SP 0702 5110]. Yields of up to 432 m^3/d have also been recorded from the base of the group in some parts of the southern margin of the Cheshire Basin, in particular from the Tarporly Siltstone (Unit A). In some cases higher yields may be due, at least in part, to upward leakage from the hydraulically connected Sherwood Sandstone aquifer.

Markedly higher yields are also obtained in some parts of south Wales and south-west England, where the marginal conglomerates are present at the base of the group. In the Cardiff area these marginal facies are carbonate aquifers and they often possess a relatively higher permeability due to the presence of solution enlarged fractures in the limestone conglomerates, breccias and calcarenites and localised dolomitisation. Where these strata overlie the Carboniferous Limestone, the two aquifers are commonly in hydraulic continuity (Waters and Lawrence, 1987). At least 25 boreholes are recorded to have penetrated the marginal facies beneath thick red mudstones in the Cardiff area, water often being reported to have been obtained from an upper sandstone in the marginal facies, referred to as the 'Lower Water Bed' (Howard, 1894; Boulton, 1910; Strahan and Cantrill, 1912). Yields are highly variable ranging from dry boreholes to 1900 m^3/d from a 200 mm borehole and 4500 m^3/d from a 12 m shaft, both at Biglis [ST 145 699 and ST 146 697 respectively]. Yields in the range of 260 to 690 m^3/d are however more common (British Geological Survey, 1986) but information is sparse as few boreholes are subject to abstraction licensing. A thin sandstone (about 1 m thick) also present in the upper part of the mudstone sequence in the Cardiff area is known as the 'Upper Water Bed' (Howard, 1894; Strahan and Cantrill, 1912). This horizon commonly only yields small amounts of water (Boulton, 1910) and in at least two cases drilling has been continued into the deeper marginal facies having obtained an inadequate supply in this horizon. Yields of about 215 m^3/d have however been obtained in several boreholes in the area (Waters and Lawrence, 1987).

Yields of up to 840 m^3/d have been obtained from boreholes penetrating the Mercia Mudstone Group in the area around Bristol. It is likely that such high yields are due to the presence of the thick Redcliffe Sandstone at the top of the marginal facies but records are insufficiently detailed to show the precise origin as in some places this sandstone is also underlain by the Dolomitic Conglomerate, a marginal facies fanglomerate which drapes the buried landscape of the Mendips and other Carboniferous anticlines south of the city.

In the vicinity of the Mendips the conglomerates of the marginal facies constitute the group's main aquifer horizon, although part of their productivity may be attributed to hydraulic continuity with overlying or underlying deposits (see Section 7.3.3.2). Green and Welch (1965) considered that the highest yields were obtainable from the conglomerates, decreasing with increasing distance from the Mendips as the conglomerates grade laterally into increasingly fine-grained sediments. The highest yield recorded in the area was 3050 m^3/d but more commonly they range from 86 to 865 m^3/d (Green and Welch, 1965; Whittaker and Green, 1983).

To the north and south of the Mendips and further to the west in the Taunton, Bridgwater and Quantock Hills areas, conglomerates are rare and groundwater is again predominantly obtained from skerries enclosed within the mudstone sequence. Yields are commonly in the range of 43 to 112 m^3/d (Green and Welch, 1965; Tubb, 1982; Edmonds and Williams, 1985) occasionally ranging up to almost 545 m^3/d (Whittaker and Green, 1983).

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8 Carboniferous minor aquifers

8.1 INTRODUCTION

The Carboniferous strata constitute the most extensive and economically important geological unit in the United Kingdom in terms of mineral resources. Although they are not normally considered to constitute major aquifers, their groundwater resources have been important to mineral resource development, industry and urbanisation. Since the mid 1900s many of the traditional high water-use industries have declined, as has the use of groundwater from Carboniferous strata; however it still remains an important local source, particularly to industry.

The geological setting, depositional history, nomenclature and lithologies of the three major subdivisions of the Carboniferous are briefly discussed in this section, as are the general properties of the aquifers and common hydraulic effects encountered in the constituent aquifers. Dinantian rocks are present at outcrop principally in Cornwall, Devon, Bristol and Mendips, south Wales, north Wales, Derbyshire and north Staffordshire, Lancashire, North Yorkshire, Northumberland and Cumbria (Figure 8.1). The Carboniferous limestones in the Derbyshire, Mendips and south Wales areas constitute major aquifers and have been previously described in detail by Allen et al. (1997). They are not discussed here.

Succeeding sections of this chapter detail the aquifer properties of each of the major subdivisions of the Carboniferous (where present) for specific areas of England and Wales. The Carboniferous aquifers have been divided into areas on the basis of geological distribution of outcrop, stratigraphy and the availability of data. The distribution of Carboniferous outcrop is shown on Figure 8.1, together with the six geographic subdivisions namely south-west England, south Wales with the Forest of Dean and Bristol area, north Wales, central England, the Pennines and northern England.

8.1.1 Nomenclature of the Carboniferous system

Much of the nomenclature used for sub-divisions of the Carboniferous came into use very early in the history of geology. The basic threefold division of strata (Carboniferous Limestone, Millstone Grit and Coal Measures) used by Conybeare and Phillips (1822) has remained in use and is approximately equivalent to the current terms Dinantian, Namurian and Westphalian (Ramsbottom et al., 1978). Green et al. (1878) provided a twofold division, with the Upper Carboniferous comprising the Millstone Grit and Coal Measures and the Lower Carboniferous containing the Carboniferous Limestone and Yoredale 'Series'. This twofold division has persisted with the Lower Carboniferous being referred to as the Dinantian Series (Munier-Chalmas and Lapparent, 1893) and, more recently, the Upper Carboniferous being referred to as the Silesian Series (van Leckwijck, 1960). In Europe a twofold division of the Dinantian, into the Tournaisian and Visean series, is widely used but these names have not gained widespread use in the United Kingdom (George et al., 1976). The Subsystem, Series and Stage subdivisions of the Carboniferous System are shown in Table 8.1.

8.1.2 General geology

The Carboniferous strata are composed of a very wide range of rock types. Dinantian lithologies range from deep basinal non-calcareous mudstones to thick massive shelf limestones, reef limestones and massive sandstones. In contrast to the predominantly carbonate Dinantian strata, Silesian sequences are generally clastic-rich, reflecting a large variety of depositional environments which ranged from alluvial fans and deltas to deep marine basins. A steady transition from the diverse environmental conditions of the late Dinantian period to more stable and uniform conditions is reflected in the widespread deposition of deltaic and fluviatile sediments in the late Silesian period. Such sediments commonly display conspicuous cyclic fining-upward sequences. A more detailed discussion of depositional environments, nomenclature, cementation, thickness variation and lithological relationships with older and younger strata for the Carboniferous Limestone, Millstone Grit and Coal Measures of England and Wales is contained in the following sections. Lithological and facies variations, hydrogeological and aquifer properties for each of the main divisions of the Carboniferous are discussed in more detail, based on geographical areas of England and Wales (Sections 8.2 to 8.7).

8.1.2.1 *Major structural events affecting the Carboniferous*

Hercynian deformation

During Late Devonian and Dinantian times a phase of north–south extension resulted in the development of grabens and

Table 8.1 Subdivisions of the Carboniferous System (after Ramsbottom et al., 1978, George et al., 1976 and Leeder, 1992).

Sub-System	Series	Stage
Silesian	Stephanian	Stephanian A, B, C Cantabrian
	Westphalian	Westphalian D Westphalian C Westphalian B Westphalian A
	Namurian	Yeadonian Marsdenian Kinderscoutian Alportian Chokierian Arnsbergian Pendleian
Dinantian	Visean	Brigantian Asbian Holkerian Arundian Chadian
	Tournaisian	Ivorian Hastarian

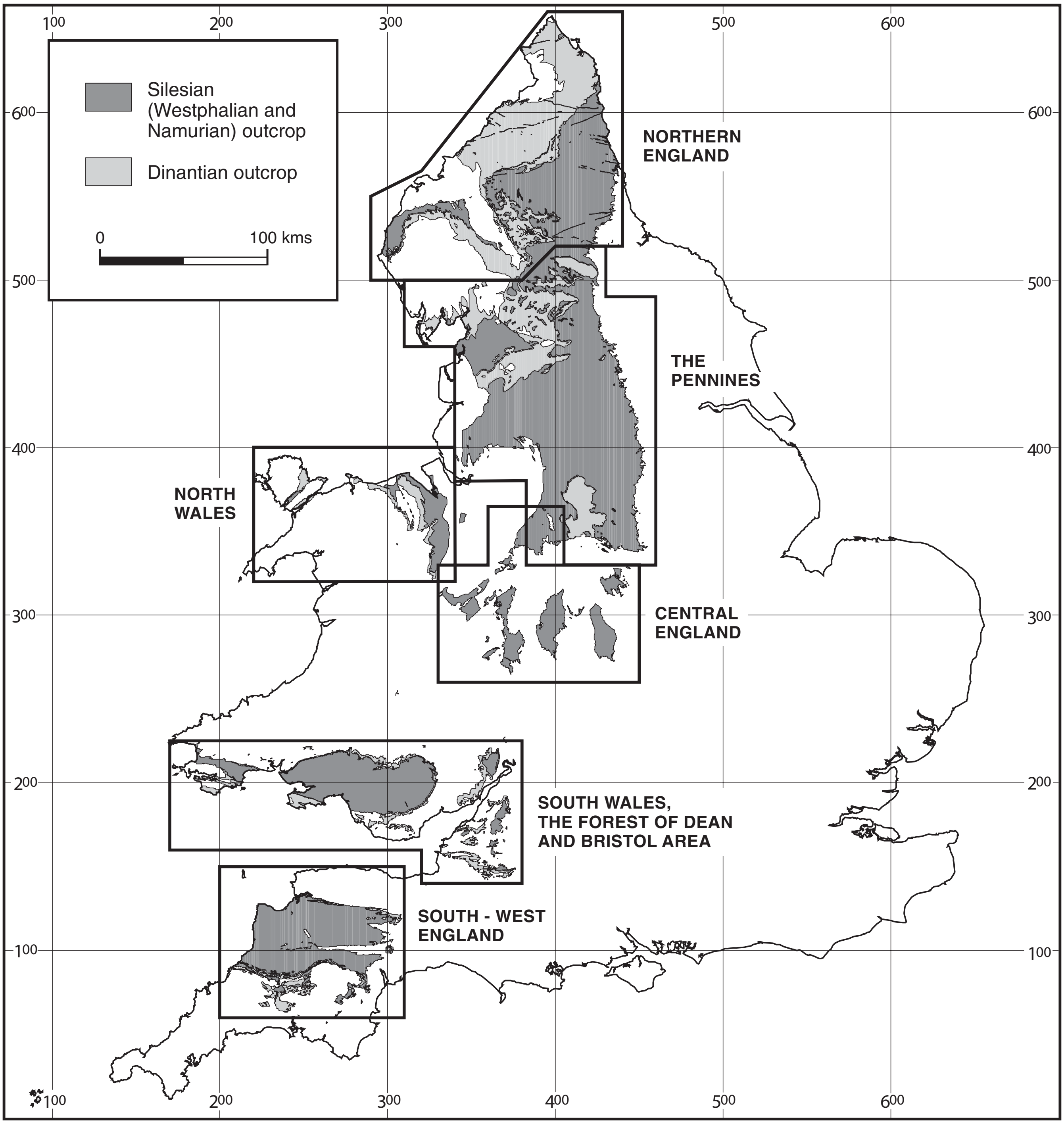


Figure 8.1 Distribution of Carboniferous outcrops in England and Wales.

half-grabens which controlled sedimentation in the central and northern parts of England. Among the features generated were stable platform blocks such as the Askrigg and Alston blocks and the Derbyshire Dome and Wales-Brabant High, all of which underwent relatively little subsidence and at times may have been emergent and subject to erosion. The platforms were separated by basins, such as the Northumberland and Stainmore troughs, the Craven Basin, and Edale and Widmerpool gulfs, these being associated with rapid subsidence (Figure 8.2). The geometry of the basins and platforms was largely controlled by pre-existing crustal structures. During Namurian and Westphalian times there was a transition to a period in which subsidence dominated, producing the Pennine Basin north of the Wales Brabant High in the former area of greatest lithospheric extension. Pulses of relatively minor compression, inversion of faults, formation of unconformities and folding become increasingly prevalent from Westphalian C to Early Permian times culminating in the end-Carboniferous to Early Permian uplift and erosion associated with the Sub-Permian Unconformity. Reactivation of basement lineaments produced reverse faults or oblique wrench faults, depending upon the orientation of the structures relative to the axis of compression. Major structures such as the South Wales Syncline and possibly the Pennine Anticline were produced by this event.

South of the Wales-Brabant High compressional deformation associated with the Variscan event may have started as early as Late Devonian and continued through to the end Carboniferous, with a broad northward migration of defor-

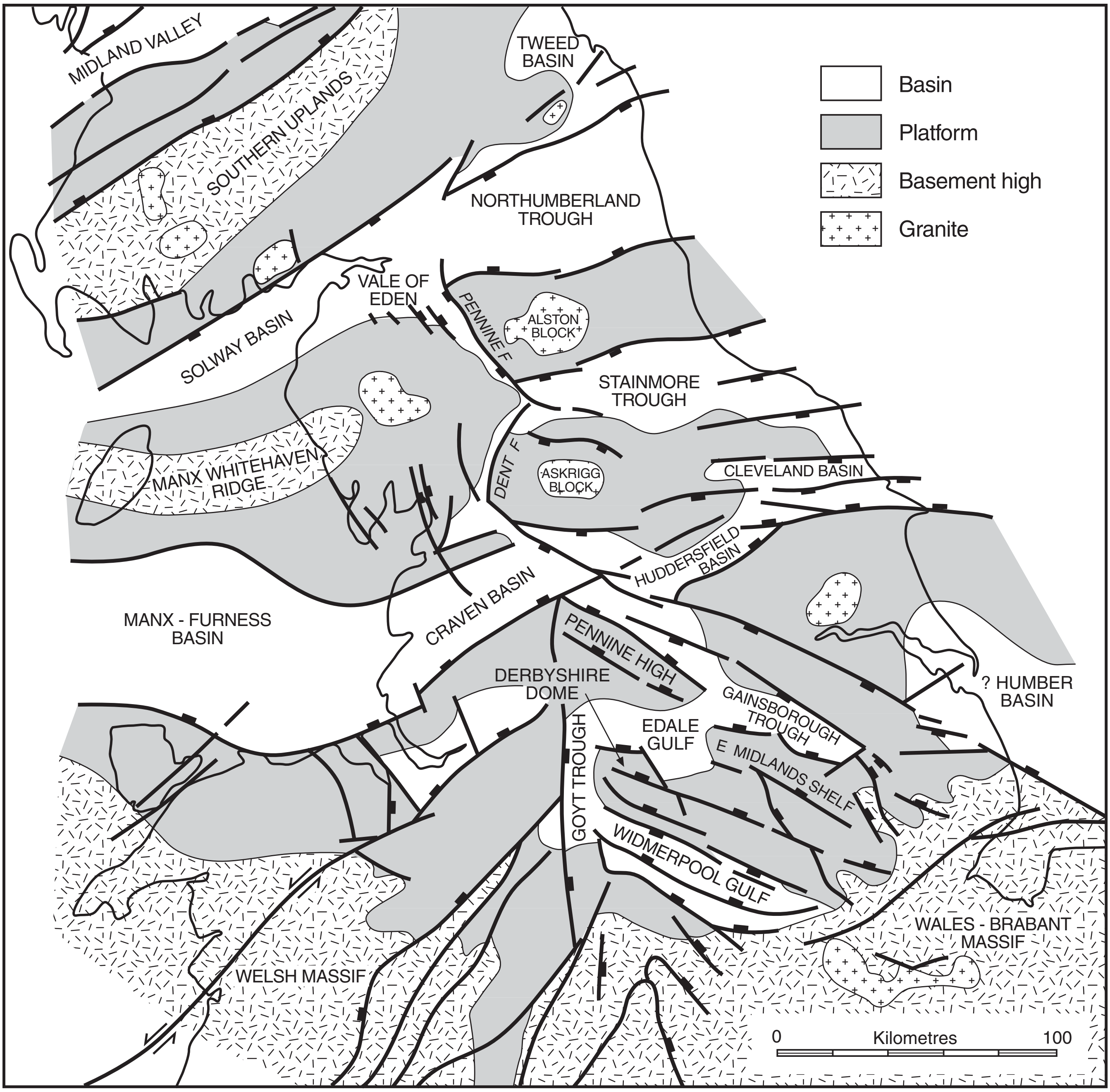


Figure 8.2 Early Carboniferous structural elements in the Midlands and northern England (after Fraser et al., 1990).

mation with time. Simplistically, the deformation has been interpreted as shallow thrust-folding generated by north-south compression. The tectonic intensity increased southwards. In south Wales the northern part of the coalfield shows relatively small disturbances, which are of Caledonian trend, whereas in the south of the coalfield and also in the Mendips there is intense folding and thrusting with convergence of folds toward the north. In north Devon there is an east–west trending anticlinorium with divergent-facing folds thought to be Silesian in age. In central Cornwall and south Devon the folding is north-facing with the recumbent folds having a slatey cleavage which dies out northwards and is thought to be Dinantian in age. In south Cornwall the thrusts and folds have a north-east trend, and are considered to be of Late Devonian age. The most southerly outcropping nappe comprises the Lizard Complex, which has been classified as an ophiolite.

In southern England, where strata of Carboniferous age are concealed beneath Mesozoic and younger strata, seismic reflection profiles have identified south-dipping thrusts, the most northerly of which is the Variscan Front, overridden by north-verging asymmetric folds.

8.1.2.2 *Dinantian (Carboniferous Limestone)*

Extent of aquifer group

Dinantian rocks are present at outcrop principally in Cornwall, Devon, Bristol and the Mendips, south Wales, north Wales, Derbyshire and north Staffordshire, Lancashire, North Yorkshire, Northumberland and Cumbria (Figure 8.1).

The thickness of Dinantian strata in Devon and Cornwall is difficult to determine due to the intense Variscan deformation and pervasive metamorphism. However, in the Boscastle and Okehampton areas it is estimated to be about

200 m thick. This is thin relative to the shelf area of the Mendips, where up to 850 m is recorded, although in turn there is a further thinning northward toward the Wales-Brabant Massif with only around 360 m at Chepstow. The Dinantian succession in south Wales is thickest in Pembrokeshire but thins to the north. The general northward shallowing towards the margins of St George's Land, uplift, erosion and other tectonic effects during, and late in, the Dinantian, are reflected in stratigraphic breaks and non-clastic nearshore facies changes.

In north Wales there is an eastward thickening of Dinantian strata from about 300 m in Anglesey to about 1150 m in the vicinity of Prestatyn. The majority of this succession is carbonate-dominated, though the conglomeratic Basement Beds occur locally up to 100 m thick at the base of the succession.

In the Craven Basin of Lancashire, Dinantian strata are highly variable depending upon the position relative to tilted blocks and basins.

In the Askrigg Block the Great Scar Limestone Group is around 230 to 275 m thick and the overlying Wensleydale Group 240 to 350 m thick.

In the Northumberland Trough, in excess of 2600 m of strata are recorded, with the Fell Sandstone Group varying from 180 to 300 m in thickness.

Correlation between current and former nomenclature

It is convenient to consider the nomenclature used for Dinantian strata separately for the areas located to the north and south of a central England and Wales divide, although approximate cross correlations can be made by use of the stages. The nomenclature used for Dinantian rocks in northern England and north Wales is shown in Table 8.2 whilst that used in south-west England and south Wales is shown in Table 8.3 (south Wales, Bristol/Mendips, Cornwall and Devon areas).

Stratigraphy and lithology

The stratigraphic relationships between the Dinantian and older and younger rocks are briefly covered here. The lithology and local stratigraphy of the Dinantian strata are covered in more detail in the discussion of individual areas (Sections 8.2 to 8.7).

In the shelf or block areas of the Derbyshire Dome, and Askrigg Block and in the Stainmore Trough Dinantian rocks rest unconformably upon Lower Palaeozoics with Devonian strata absent. In north Wales Dinantian carbonates rest unconformably upon Precambrian (Mona Group) to Devonian (Old Red Sandstone) rocks. In the Alston Block the Dinantian strata rest unconformably upon the Weardale Granite (Table 8.2).

In the Bristol, Mendips and south Wales areas and in the Northumberland Trough, Dinantian rocks rest conformably upon sandstones of the Upper Old Red Sandstone. In south-west England the Dinantian is conformably underlain by Devonian strata (Table 8.3).

In the basinal areas of Devon and Cornwall and the central Pennines there is a conformable transition from Dinantian to Namurian mudstones. The top of the Dinantian strata is defined everywhere as the base of the Cravenoceras leion Marine Band. However, in the block areas of the northern Pennines the transition is marked by continued deposition of 'Yoredale facies' deltaic strata in which this diagnostic marine band is absent.

The most common cement found in the Dinantian limestones is calcite. The lowermost carbonate of Dinantian age in the Bristol and Mendips area, the Black Rock Limestone, becomes increasingly dolomitised from north of Bristol towards Chepstow and similarly the Lower Main Limestone of south Wales becomes increasingly dolomitised toward the east. Dinantian limestones are also recorded to be dolomitised in north Wales. Replacement of limestone by dolomite and silica is evident locally in the Askrigg Block and Craven Basin. The dolomite replacement is dominantly late, though minor early diagenetic replacement is recorded. Chert is an early replacement. Dolomitisation and silicification may be particularly common in limestones present beneath thick mudstone sequences which may have impeded the upward flow of silica- and magnesium-rich fluids.

Dissolution of carbonates to produce extensive cavern systems and other karstic features much enhances water flow rates.

Structural depositional controls

During latest Devonian to earliest Dinantian times a phase of north–south crustal stretching resulted in the development in the north Pennines of large blocks, e.g. the Askrigg and Alston blocks, and in the central and southern Pennines in a tilted block and basin topography. The blocks are typically associated with the deposition of platform shallow water carbonates, whereas the intervening basins are characterised by deeper water mudstones with ramp limestones, reflecting a very gently sloping transition from platform to basin.

During much of the Dinantian sediment deposition occurred in two separate areas to the north and south of a land area stretching across central Wales to eastern England (St George's Land and the London-Brabant High) (Cope et al., 1992). The various structural elements which exercised control on deposition to the north of the land mass during the Dinantian are shown in Figure 8.2. A more detailed account of palaeogeography and facies distribution over the whole of British Isles at various stages of the Dinantian is provided by Cope et al. (1992).

Igneous activity

Tuffs, agglomerates and spilitic lavas of the Tintagel Volcanic Formation of the Tintagel Group occur in north Cornwall and south Devon. The lavas are commonly brecciated, locally amygdaloidal and pumiceous. Minor volcanism occurred in the Bristol and Gloucester areas, producing olivine-basalt lavas and tuffs.

The upper part of the Dinantian succession in Derbyshire includes several olivine basalt lavas and tuffs, e.g. the Millers Dale Lavas and Matlock Lavas. The lavas are notable as being almost impermeable to water migration. The tuffs are usually green- or brown-weathered, comprising glass lapilli in a matrix of volcanic dust and calcite. The extrusive sequences are relatively thin, each only a few tens of metres thick.

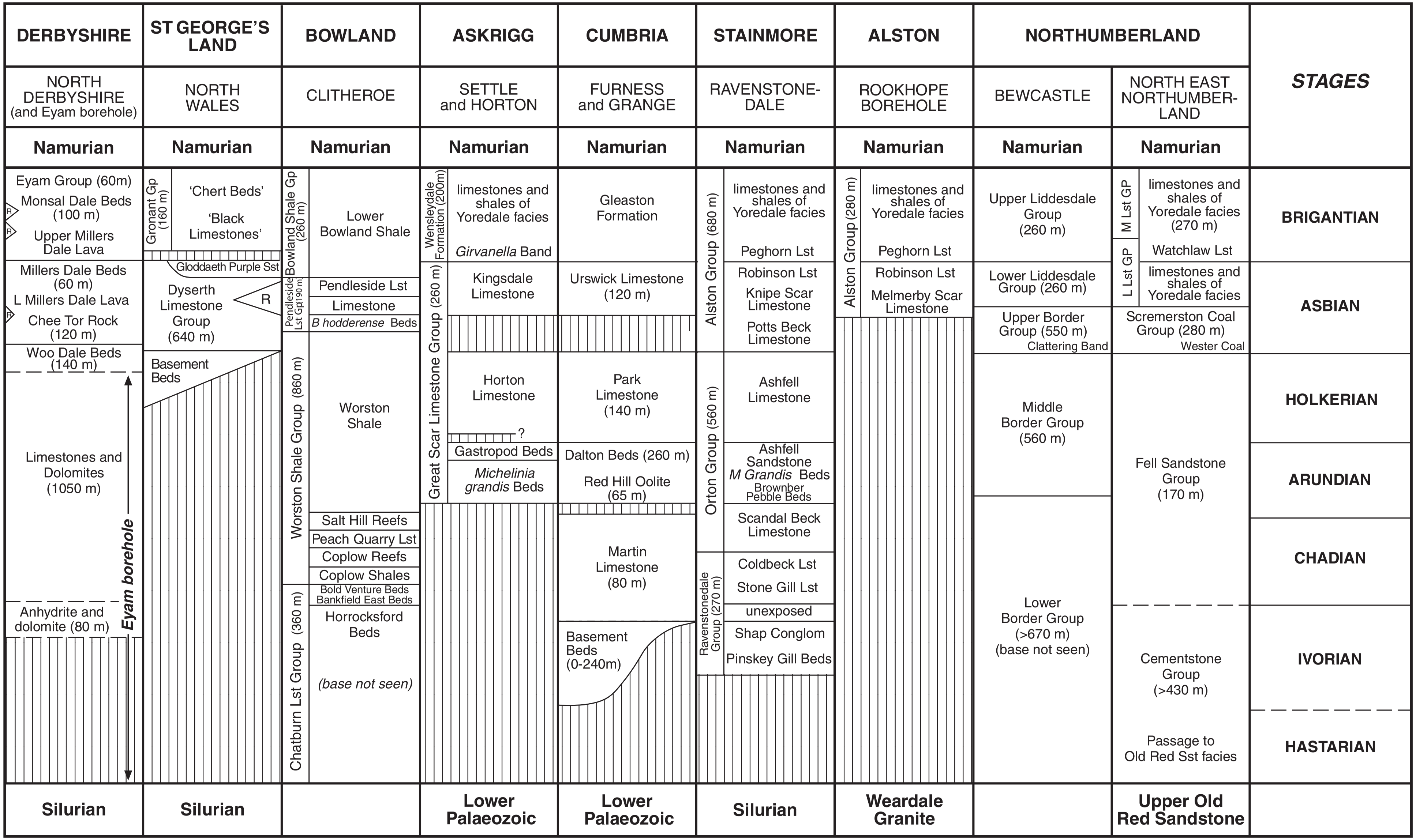
Olivine basalts occur in the Northumberland Trough with the Kelso Lavas up to 120 m thick in the Cheviots, and the Cockermouth Lavas up to 100 m thick in Cumbria.

8.1.2.3 *Namurian (Millstone Grit Group)*

Extent of aquifer group

The Millstone Grit mainly outcrops in the central Pennines of Yorkshire and Lancashire, but extends as far south as the East Midlands, north Staffordshire and south and north-east Wales (Figure 8.3).

The equivalent of the Millstone Grit facies is stratigraphically classed in the northern Pennines and north-east



DERBYSHIRE	ST GEORGE'S LAND	BOWLAND	ASKRIGG	CUMBRIA	STAINMORE	ALSTON	NORTHUMBERLAND		*STAGES*
NORTH DERBYSHIRE (and Eyam borehole)	NORTH WALES	CLITHEROE	SETTLE and HORTON	FURNESS and GRANGE	RAVENSTONE-DALE	ROOKHOPE BOREHOLE	BEWCASTLE	NORTH EAST NORTHUMBER-LAND	
Namurian	**Namurian**	**Namurian**	**Namurian**	**Namurian**	**Namurian**	**Namurian**	**Namurian**	**Namurian**	
Eyam Group (60m) Monsal Dale Beds (100 m) Upper Millers Dale Lava	Gronant Gp (160 m) 'Chert Beds' 'Black Limestones' Gloddaeth Purple Sst	Bowland Shale Gp (260 m) Lower Bowland Shale	Wensleydale Formation (200m) limestones and shales of Yoredale facies *Girvanella* Band	Gleaston Formation	Alston Group (680 m) limestones and shales of Yoredale facies Peghorn Lst	Alston Group (280 m) limestones and shales of Yoredale facies Peghorn Lst	Upper Liddesdale Group (260 m)	M Lst GP limestones and shales of Yoredale facies (270 m) Watchlaw Lst	**BRIGANTIAN**
Millers Dale Beds (60 m) L Millers Dale Lava Chee Tor Rock (120 m)	Dyserth Limestone Group (640 m) R	Pendleside Lst Gp 190 m Pendleside Lst Limestone *B hodderense* Beds	Great Scar Limestone Group (260 m) Kingsdale Limestone ▥	Urswick Limestone (120 m) ▥	Robinson Lst Knipe Scar Limestone Potts Beck Limestone	Robinson Lst Melmerby Scar Limestone	Lower Liddesdale Group (260 m) Upper Border Group (550 m) Clattering Band	L Lst GP limestones and shales of Yoredale facies Scremerston Coal Group (280 m) Wester Coal	**ASBIAN**
Woo Dale Beds (140 m) Limestones and Dolomites (1050 m) *Eyam borehole*	Basement Beds ▥	Worston Shale Group (860 m) Worston Shale	Horton Limestone ▥ ?	Park Limestone (140 m)	Orton Group (560 m) Ashfell Limestone	▥	Middle Border Group (560 m)	Fell Sandstone Group (170 m)	**HOLKERIAN**
	▥		Gastropod Beds *Michelinia grandis* Beds	Dalton Beds (260 m) Red Hill Oolite (65 m) ▥	Ashfell Sandstone *M Grandis* Beds Brownber Pebble Beds	▥	Lower Border Group (>670 m) (base not seen)		**ARUNDIAN**
	▥	Salt Hill Reefs Peach Quarry Lst Coplow Reefs Coplow Shales Chatburn Lst Group (360 m) Bold Venture Beds Bankfield East Beds	▥	Martin Limestone (80 m)	Scandal Beck Limestone Ravenstonedale Group (270 m) Coldbeck Lst Stone Gill Lst	▥			**CHADIAN**
Anhydrite and dolomite (80 m) ▥	▥	Horrocksford Beds *(base not seen)*	▥	Basement Beds (0-240m) ▥	unexposed Shap Conglom Pinskey Gill Beds ▥	▥		Cementstone Group (>430 m)	**IVORIAN**
▥	▥		▥	▥	▥	▥		Passage to Old Red Sst facies	**HASTARIAN**
Silurian	**Silurian**		**Lower Palaeozoic**	**Lower Palaeozoic**	**Silurian**	**Weardale Granite**		**Upper Old Red Sandstone**	

▥ *Hiatus*

Table 8.2 Dinantian stratigraphic successions in northern England and north Wales (after George et al., 1976, Mitchell, 1978 and Leeder, 1992).

	'CULM' BASIN			SOUTH WALES		BRISTOL / MENDIPS	
STAGES	CORNWALL Boscastle Launceston	N DEVON Barnstaple Bideford	NE DEVON Westleigh Bampton	S WALES Gower	S WALES Clydach Valley	MENDIPS Burrington	BRISTOL Avon Gorge
	NAMURIAN	NAMURIAN	NAMURIAN	NAMURIAN	NAMURIAN	TRIASSIC	NAMURIAN
BRIGANTIAN	Fire Beacon Chert Formation *BUCKATOR FORMATION*: Upper Limestone	Black Shale Formation Chert Formation	Upper Westleigh Limestone	Oystermouth Beds (20 metres) Oxwich Head Limestone (90 metres)	▥	(not seen) Hotwells Limestone (30 metres)	Hotwells Group (210m): Upper Cromhall Sandstone
ASBIAN			Lower Westleigh Limestone	▥		▥	Hotwells Limestone ▥
HOLKERIAN	Lower Limestone	Basement Formation		Hunts Bay Oolite (260 metres) ? ▥	Limestones with oolites	Clifton Down Limestone (220 metres)	Clifton Down Group (300m): Upper Clifton Down Limestone ▥
ARUNDIAN	*TINTAGEL FORMATION*: Trambley Cove Formation Tintagel Volcanic Formation			High Tor Limestone ▥	▥	Burrington Oolite (230m): Quarry 2 Lst Rib Mdst Aveline's Hole Limestone ▥ ?	Lower Clifton Down Limestone Upper C D Mdst Goblin Combe Oolite ▥
CHADIAN	Barras Nose Formation			Caswell Bay Mdst Caswell Bay Oolite (35 metres) ▥ ?	Llanelly Fm (18 metres) Gilwern Oolite (12 metres) Clydach Beds	Ham Mdst Gully Oolite Quarry 3 Lst Black Rock Limestone (270 metres)	Lower C D Mdst Gully Oolite Suboolite Bed ▥
IVORIAN		Pilton Beds		Penmaen Burrows Limestone (300 metres) Cefn Bryn Shales (110 metres)	Blaen Onnen Oolite (30 metres) Pwll-y-Cwm Oolite (7 metres) Lower Limestone Shale (12 metres)	Lower Limestone Shale (150 metres)	Black Rock Limestone (130 metres) Lower Limestone Shale (70 metres)
HASTARIAN	Yeolmbridge Formation						▥ Shirehampton Beds (35 metres)
	DEVONIAN	DEVONIAN	DEVONIAN	Upper Old Red Sandstone	Upper Old Red Sandstone	Upper Old Red Sandstone	Upper Old Red Sandstone

Table 8.3 Stratigraphic succession in the Dinantian of south-west England and south Wales (after George et al., 1976 and Leeder, 1992).

England, including the Askrigg and Alston blocks and intervening Stainmore Trough, as part of the Stainmore Group.

The Millstone Grit is estimated to be up to 2100 m thick in Lancashire and 1800 m in West Yorkshire, thinning southwards to less than 200 m in the East Midlands and north-east Wales. It is completely absent in the area of the Wales-Brabant High, through central Wales and the south Midlands. In south Wales a maximum thickness of about 275 m is attained, and the sequence is most complete in the Gower area, with marked thinning northwards towards the Wales-Brabant High and eastwards towards the Usk Anticline.

The Pendle Grit Formation is an important unit which varies in thickness from about 200 m to 475 m in the Craven Basin, but is absent in the southern Pennines and further south. Individual sandstone members of the Millstone Grit are variable in thickness though rarely exceed 30 m.

The Stainmore Group is about 500 m thick in the Stainmore and Northumberland troughs and 300 m thick on the Alston Block.

Correlation between current and former nomenclature

The Millstone Grit Group was formerly referred to as the Millstone Grit Series, a chronostratigraphical term which encompassed all strata of Namurian age. The current nomenclature refers to only Namurian strata of the Millstone Grit facies; older Namurian strata, being composed of predominantly argillaceous strata, are not generally water-bearing. With a few exceptions, such as the Pendle Grit Formation, the group has not been formally subdivided into formations. Individual sandstones are typically given local names, such that regionally extensive sandstones may have numerous names. This is a particular problem with sandstones of Marsdenian age. The Roaches and Ashover grits of the south Pennines are synonymous and are considered to correlate with the Guiseley Grit of the central Pennines. The

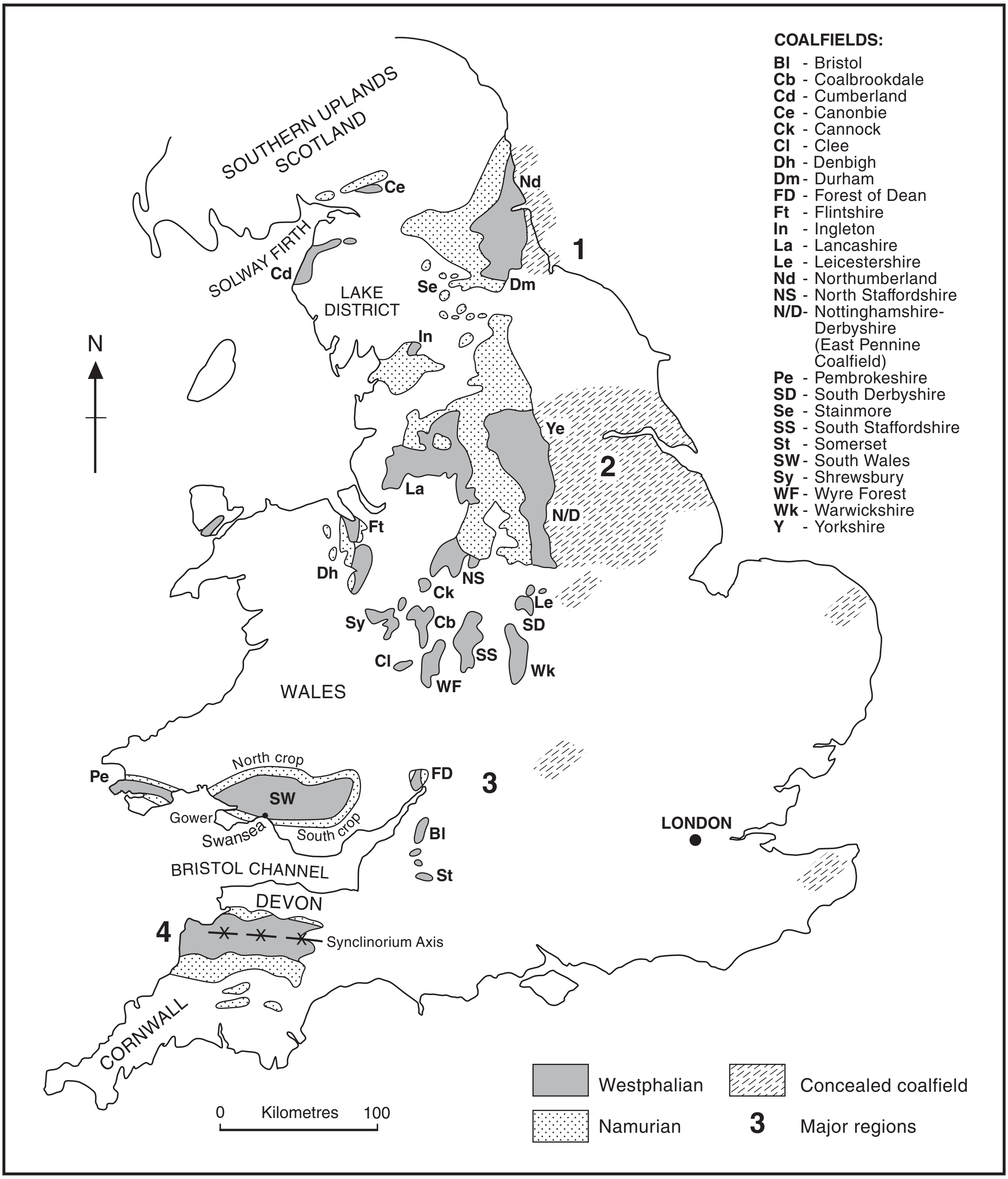


Figure 8.3 Distribution of Silesian outcrops in England and Wales.

Chatsworth Grit of the south Pennines is the same age as, and has been correlated with, the Huddersfield White Rock of the central Pennines. A correlation of Millstone Grit horizons in the Craven Basin and areas to the north is shown in Figure 8.4. The correlation of Millstone Grit sandstones which are lithologically quite similar is dependent upon the position of the sandstones relative to known marine bands. Where this relationship is equivocal, the identification of sandstone names can be uncertain. Sandstones of Kinderscoutian age are particularly difficult to correlate over large areas and the use of a chronostratigraphical name, the Kinderscout Grit, is still commonly used.

The Stainmore Group equates to the former Upper Limestone Group and Millstone Grit.

Lithology and stratigraphy

The stratigraphic relationships between the Namurian and older and younger rocks are briefly covered here. The litho-

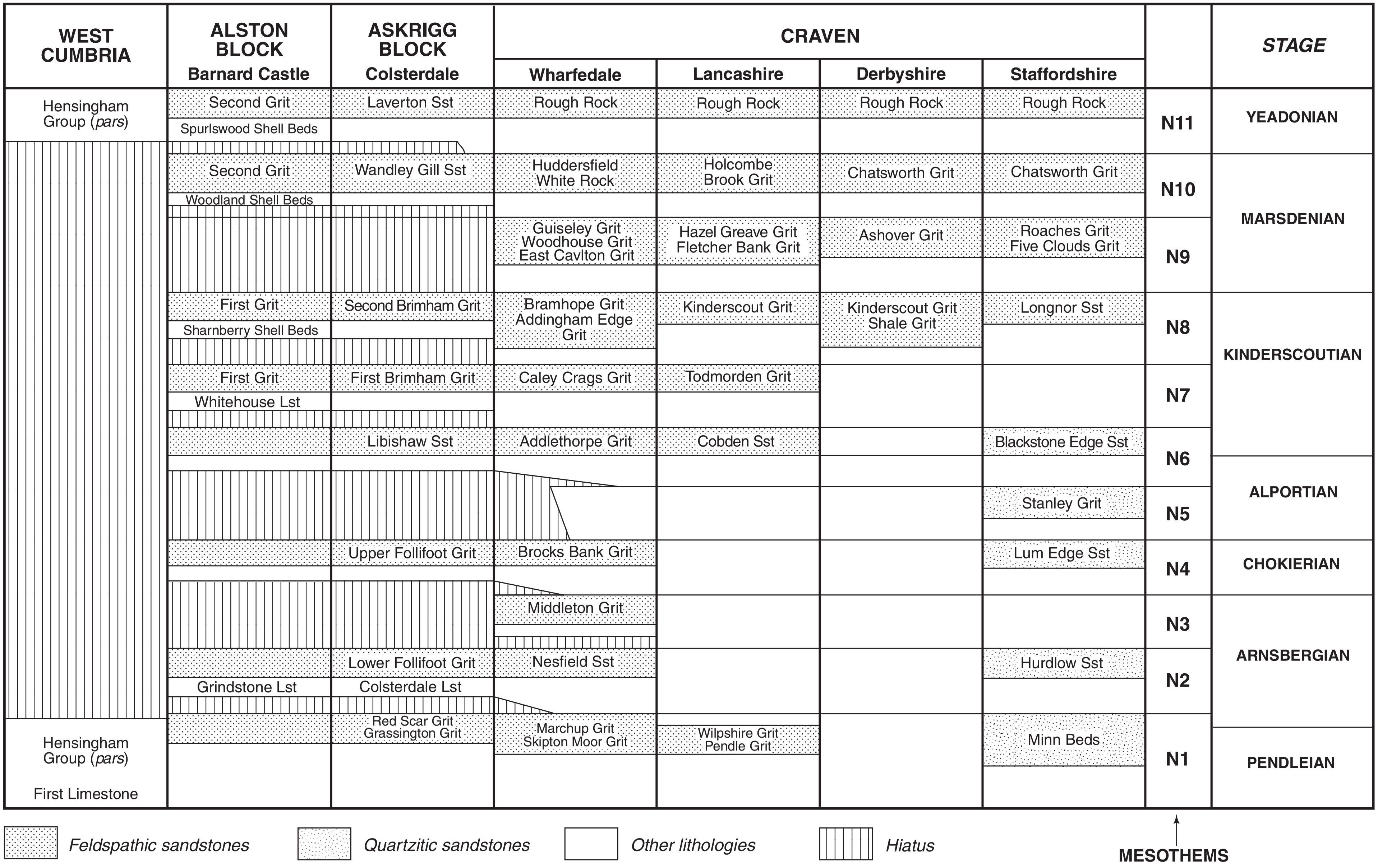


Figure 8.4 Correlation of Millstone Grit horizons in the Craven Basin and areas to the north (after Ramsbottom et al., 1978).

logy and local stratigraphy of the Namurian strata are covered in more detail in the discussion of individual areas. (Sections 8.2 to 8.7).

The base of the Millstone Grit is taken as the first incoming of dominantly feldspathic sandstones in a sequence of Namurian age. This base is markedly diachronous, with the incoming of thick sandstones occurring earlier, during the Pendleian, in the north with deposition of the Pendle Grits, and later, during the Marsdenian, in the Midlands with deposition of the Ashover and Roaches grits and Yeadonian in north Wales (Figure 8.5). The group typically rests conformably upon thick mudstones of the Bowland Shale Group in the central Pennines or Edale Shale Group in the south Pennines and Midlands. In south Wales the Millstone Grit rests unconformably upon strata ranging possibly from Precambrian to Dinantian age.

The Stainmore Group, which includes strata of Millstone Grit facies, encompasses all strata of Namurian age, the base is taken at the base of the Great Limestone, or the Main Limestone on the Askrigg Block.

The top of the Millstone Grit Group and Stainmore Group is taken as the base of the Subcrenatum Marine Band and is overlain by Coal Measures facies. For the Millstone Grit the Subcrenatum Marine Band commonly occurs immediately above the Rough Rock.

Millstone Grit sandstones are typically cemented by quartz overgrowths. Generally, finer grained sandstones display more authigenic quartz. Intergranular authigenic clays are variably developed with kaolinite and illite or sericite being the common components. These clays may often be produced by the alteration of feldspar grains, which may result in development of a grain dissolution porosity. Coarse-grained arkosic sandstones may be particularly prone to diagenesis and development of secondary porosity. Rarely, sandstones which have been deposited in a marine environment may have a more calcite-rich cement which, if subsequently dissolved, can result in relatively high porosities.

More generally, however, sandstone fabrics are closely packed with quartz overgrowths and pressure welding resulting in low intergranular porosity. Fluid migration is principally through fractures and joints.

Limestones of the Stainmore Group often are partially or completely recrystallised with development of microspar.

Structural depositional controls

Crustal extension, which acted as a dominant control on sedimentation during the Dinantian, is considered to have diminished during the Namurian. The primary tectonic control on stratal thickness instead was the development of a broad subsiding basin, the Pennine Basin, with greatest subsidence rates and hence thicknesses occurring in Lancashire and north Staffordshire. However, there are still dramatic thickness variations in individual sandstones and the Millstone Grit as a whole which, in part, is due to the infilling of a marked topography developed during the Dinantian but also reflects continued structural activity. This is evident on the Askrigg Block as two prominent unconformities within Pendleian and Arnsbergian strata.

In the Gower area, where the Namurian in south Wales is thickest (about 275 m) and most complete, the sequence is basinal in character, consisting of a thick sequence of argillaceous strata with sandstones only occurring in the upper part, at the top of the Chokierian and Marsdenian. The Namurian thins markedly northwards towards the Wales-Brabant High and eastwards towards the Usk Anticline, overlapping successively older Dinantian and Devonian strata. In the north and east the succession consists of alternating sandstones and marine shales, with all but the uppermost horizons absent in the extreme west and east (Ramsbottom et al., 1978).

Namurian strata are absent in the Forest of Dean. The Bristol area constituted a small basin, separated from the main area of deposition in south Wales in which predominantly sandstones were laid down, with minor marine intercalations (Ramsbottom et al., 1978).

Igneous activity

Volcanic rocks of Namurian age are very limited in extent but have been detected in boreholes in the East Midlands as altered tuffs and agglomerates along with lavas and dolerite sills.

8.1.2.4 *Westphalian (Coal Measures Group)*

Extent of aquifer group

The Coal Measures occur in a series of coalfields which can be subdivided into those of the Pennine Basin developed between the Wales-Brabant High and the Southern Uplands of Scotland (i.e. Northumberland and Durham, Cumberland, Lancashire, north Wales, Yorkshire, Nottinghamshire and north Derbyshire, north and south Staffordshire, Leicestershire and south Derbyshire and Warwickshire) and those which developed south of the Wales-Brabant High (i.e. south Wales, Forest of Dean, Bristol and Somerset and Kent) (Figure 8.3).

The Coal Measures Group is thickest in the North Staffordshire and Lancashire coalfields with up to 1600 m recorded in the vicinity of Stoke, comprising 650 m of Lower Coal Measures, 600 m of Middle Coal Measures and 350 m of Upper Coal Measures. In the Lancashire Coalfield there are about 720 m of Lower Coal Measures and 650 m of Middle Coal Measures. The thickness diminishes rapidly southwards towards the Wales-Brabant High, so that in the South Staffordshire Coalfield there is a total of only 100 to 150 m. In south Wales the maximum thickness (up to 900 m) of Lower and Middle Coal Measures occurs in the western and south-western part of the Coalfield in the Ammanford-Swansea area. There is progressive attenuation to the east giving a thickness of about 200 m on the eastern outcrop near Pontypool. The main stratigraphic features are however present throughout the coalfield where the Pennant Measures form the high ground over the central part of the coalfield, ranging in thickness from in excess of 1500 m in the west to about 600 m in the north-east and east (Leeder, 1992). Of these total thicknesses, sandstones constitute about 900 m in the west thinning to 600 m in the Taff valley and 240 m in the east (Holliday, 1986). Corresponding thickness ranges for the Lower and Middle Coal Measures are about 300 m to less than 80 m and about 550 m to less than 120 m respectively.

Correlation between current and former nomenclature

The Coal Measures have historically been subdivided into Lower, Middle and Upper Coal Measures. The bases of the units are defined as the bases of the Subcrenatum, Vanderbeckei and Cambriense marine bands, respectively. This nomenclature has been continued, with the exception of a redefinition of the Upper Coal Measures. Formerly, the Upper Coal Measures comprised all Carboniferous strata present above the Cambriense Marine Band. These included the dominantly red measures of the Midlands which either lack or have only thin coal seams and instead contain widespread sandstones (especially in the south). These red measures are quite untypical of the Coal Measures facies.

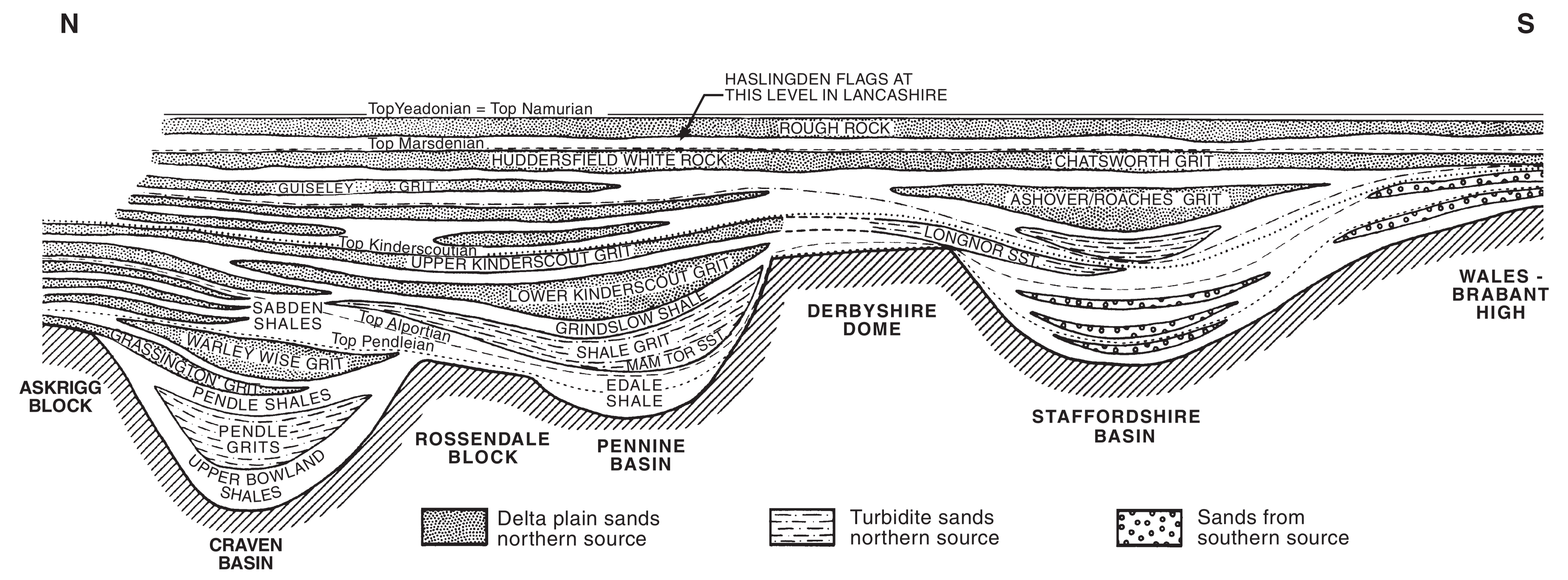


Figure 8.5 The distribution of major sandstones and shale intervals of the Millstone Grit in the Pennines and central England (after Collinson, 1988).

Currently, the red strata have been assigned to a separate group, the Barren Measures or Warwickshire Group and the Upper Coal Measures is used for strata of typical Coal Measures facies. In south Wales, where no significant red beds are present, the Pennant Measures equate to the Upper Coal Measures in the Pennine Basin.

Stratigraphy and lithology

The stratigraphic relationships between the Westphalian and older and younger rocks are briefly covered here. The lithology and local stratigraphy of the Westphalian strata are covered in more detail in the discussion of individual areas. (Sections 8.2 to 8.7).

The Coal Measures generally rest conformably upon Namurian strata (the Millstone Grit Group or Stainmore Group). However they onlap onto the Wales-Brabant High so that the Coal Measures in Kent rest unconformably upon Dinantian or Devonian strata, in Bristol and Somerset upon Namurian or Dinantian beds, and in south Staffordshire upon Silurian to Devonian strata. Upper Coal Measures unconformably overlie the Carboniferous Limestone in the centre of the Forest of Dean syncline.

In the Midlands the Coal Measures are typically overlain conformably by strata of the Barren Measures Group, whereas in northern England and to the south of the Wales-Brabant High they are unconformably overlain by Permo-Triassic strata.

Coal Measures sandstones are typically cemented by quartz overgrowths. Intergranular authigenic clays produced largely by the alteration of feldspars are variably developed with kaolinite and illite or sericite being the common components. Sandstone fabrics are generally closely packed with quartz overgrowths and pressure welding resulting in low intergranular porosity. Fluid migration is principally through fractures and joints.

Structural depositional controls

The broad subsidence of the Pennine Basin, initiated during the Namurian, continued to exert a regional control, with the greatest thicknesses in the area of greatest subsidence in Lancashire and north Staffordshire. However, this subsidence coexisted with small-scale and pulsatory phases of localised extension and compression which reactivated major basement lineaments, often with components of strike slip displacements depending upon the orientation of the basement lineaments in relation to the stress fields. These locally produced minor unconformities at the Pennine Basin margin and folds towards the centre of the basin.

In south Wales, the Carboniferous strata were deposited to the south of the Wales-Brabant High which remained emergent throughout the period and hence exerted a strong influence on the nature of deposition and provided a major source of material. The early Westphalian (Lower and Middle Coal Measures) depositional conditions were generally similar to those of the late Namurian. During the Westphalian C stage, a major change in depositional conditions occurred, giving rise to thick fluvial sandstones derived from a rapidly rising Hercynian fold belt to the south. Deposition occurred in the channels and on floodplains of northerly flowing streams, transporting immense volumes of lithic material into the subsiding South Wales Basin (Leeder, 1992).

In the Bristol area, limited thicknesses of Westphalian A and B are present but the Upper Coal Measures (Westphalian C and D) are considerably thicker. The Coal Measures in this area are largely obscured by younger Triassic strata.

Igneous activity

Volcanic activity at the time of the deposition of the Lower Coal Measures is evident from boreholes in the East Midlands. These prove local extrusions and intrusions of olivine basalt up to 150 m thick.

8.1.2.5 *Westphalian/Stephanian (Barren Measures or Warwickshire Group)*

Extent of aquifer group

The Barren Measures Group is essentially limited to the southern margin of the Pennine Basin within the Midlands, extending as far north as south Lancashire. It is estimated to be up to 1200 m thick in north Staffordshire and Warwickshire and 300 to 500 m thick in south Staffordshire.

A prominent, but poorly productive, unit is the Etruria Formation, which is up to 300 m thick in north Staffordshire, 30 to 150 m in Warwickshire and 60 to 200 m in south Staffordshire.

The Halesowen Formation is about 70 to 150 m thick in south Staffordshire, and 70 to 130 m in Warwickshire. The equivalent strata are 150 m thick in north Staffordshire.

The Salop Formation is approximately 200 to 360 m thick in the West Midlands, of which the Alveley Member is 150 to 275 m thick in Shropshire and 50 to 140 m thick in south Staffordshire. The Enville Member is 100 to 275 m thick in the West Midlands.

The Meriden Formation of Warwickshire, the lower part of which equates to the Salop Formation, is in total about 730 m thick. The typically poor permeability of the Barren Measures Group in the Midlands can have a hydrogeological significance in that water level rebound (resulting from mines closures) cannot affect overlying aquifers. This contrasts with other areas where younger aquifers are in hydraulic contact with the Coal Measures. Combined with the fact that the productive Coal Measures may have been mined nearly to the base of the younger aquifers, this allows water levels to rise into the upper groundwater system.

Correlation between current and former nomenclature

The stratigraphical nomenclature of the Upper Carboniferous red-bed succession has become very confused with similar names employed for different intervals. The current lithostratigraphy is summarised separately for the West and East Midlands in Section 8.5 and Table 8.6. Historically these red beds have been referred to as Upper Coal Measures, although now this term is restricted to strata of grey Coal Measures facies present above the Cambriense Marine Band.

Stratigraphy and lithology

The stratigraphic relationships between the Barren Measures Group and older and younger rocks are briefly covered here. The lithology and local stratigraphy of the strata are covered in more detail in the discussion of individual areas (Sections 8.2 to 8.7).

The Barren Measures generally rest conformably upon the Coal Measures Group. The base of the group, taken as the base of the Etruria Formation, is markedly diachronous, occurring earlier along the southern margins of the Pennine Basin, e.g. during the Duckmantian (Westphalian B) in south Staffordshire and possibly as late as Westphalian D in north Staffordshire. The group is overlain unconformably by Permo-Triassic strata.

Typically, sandstones of the Barren Measures have a carbonate cement; for example, sandstones of the Salop Formation usually have an abundant, early calcite cement.

Unweathered, the sandstones can be very hard, though loss of the calcite cement due to weathering often causes them to be very friable at outcrop.

Structural depositional controls

During the Upper Carboniferous, the effects of Variscan deformation became increasingly apparent with pulses of north-west–south-east to east–west compression dominating. This resulted in reactivation of basement lineaments and unconformities, notably at the base of the Halesowen and Clent formations. The unconformities are only locally developed in the Welsh borders, south Staffordshire and Warwickshire, passing northwards into conformable sequences in the basin depositional centre. The uplift and erosion of blocks along the margin of the Wales-Brabant High provided localised sediment sources for some of the late Carboniferous strata. The Variscan deformation culminated at the end of the Carboniferous in a phase of regional uplift and erosion which produced the sub-Permian unconformity.

Igneous activity

In south Staffordshire there was a prominent phase of igneous activity at the time of the deposition of the Etruria Formation. This caused intrusion of alkaline dolerite sills; notably the Rowley Regis Lopolith which is up to 100 m thick. Volcanic material is rare, but includes a single volcanic pipe and associated agglomeratic debris flow deposits at Barrow Hill.

8.1.2.6 *Culm (Namurian and Westphalian)*

Extent of aquifer group

The Culm is limited to Devon, Cornwall and west Somerset. Its thickness often cannot be readily determined due to structural complexities and poor exposure. Where known, the lower Crackington Formation is estimated to be 300 to 1500 m thick and the overlying Bude Formation is up to about 1300 m thick.

Correlation between current and former nomenclature

The terminology is that of the Geological Society special report for the Silesian and Dinantian (George et al., 1976; Ramsbottom et al., 1978). The Culm (or Culm Measures) covers strata of both Namurian and Westphalian age. The Crackington Formation is largely Namurian whilst the Bude and Bideford formations are Westphalian.

Stratigraphy and lithology

The stratigraphic relationships between the Culm and older and younger rocks are briefly covered here. The lithology and local stratigraphy of the strata are covered in more detail in the discussion of individual areas (Sections 8.2 to 8.7).

The lower part of the Culm, the Crackington Formation, is considered to rest disconformably upon Dinantian strata with Pendleian strata absent, though in the Exeter and Newton Abbott districts the formation rests conformably upon Dinantian strata, the Teign Chert. The relationship of the upper part of the Culm (the Bude Formation) with younger strata is unknown.

Structural depositional controls

Sediment deposition in the region was controlled by the Culm Basin positioned to the south of the St George's landmass which persisted throughout the Carboniferous period. Dinantian strata consist predominantly of basinal facies, mainly non-calcareous mudstones and cherts with a few local limestones. Dinantian successions in the area are invariably thin compared to nearby shelf sequences, probably due to slow subsidence and distances from shorelines (George et al., 1976). Basinal conditions also predominated during Silesian times, with turbiditic sandstone and interbedded shales generally considered to be Namurian and cyclic massive sandstones and mudstones of a more paralic origin to be Westphalian.

Igneous activity

No volcanic rocks are associated with the Culm Measures.

8.1.3 General hydrogeology

At first sight there would appear to be a marked similarity in the aquifer characteristics of all the Carboniferous strata. The complex depositional history and variable lithologies present in the sequence create a multi-layered series of aquifers in which the limestones or arenaceous horizons act as aquifers, with intervening argillaceous horizons acting as aquicludes or aquitards. There are however distinct differences between the properties of the limestones which act as aquifers in the Carboniferous Limestone and the sandstones and grits of the Silesian strata. In addition coal mining has considerably modified the properties of the Coal Measures. Thus, despite similarities, there are sufficient differences between the three main divisions of the Carboniferous to justify separate consideration of their aquifer properties. It should be noted that dry and low yielding boreholes are of widespread occurrence; however, there are very few test data for these, and hence pumping test results are biased towards higher yielding sources.

8.1.4 Controls on aquifer properties

8.1.4.1 *Lithology*

The Carboniferous sequence consists predominantly of alternations of arenaceous (sandstones/grit) or limestone horizons with argillaceous (mudstone or shale) horizons. The primary porosity of Silesian arenaceous and argillaceous strata are similar, being commonly of the order of 10 to 15%, but limestones are often much lower. The permeability is however generally greatest in sandstone and grit horizons varying according to the degree (and type) of cementation. In all strata both primary porosity and permeability generally decrease with depth due to the greater weight of overburden, compaction and increased cementation (Gray et al., 1969). At shallow depths, the effects of weathering commonly greatly increase both porosity and permeability, particularly in arenaceous strata.

8.1.4.2 *Fractures*

In the general absence of significant intergranular permeability in most Carboniferous strata, groundwater predominantly moves through joints and fractures. Although discontinuities do occur in the more argillaceous strata, joints and fractures occur mainly within limestones, sandstones and grits and it is these strata which act as aquifers. Borehole yields depend on penetrating one or more fracture horizons and the degree, size and extent of interconnection of fractures within those horizons. Initial yields may not be sustainable where the degree of lateral interconnection is poor. Low yielding or dry sandstones and limestones are by no means uncommon in the absence of fractures and, where very well cemented, such strata (particularly limestones) can act as aquicludes.

8.1.4.3 *Faulting*

The Carboniferous strata are often extensively faulted, with associated fracturing, which may increase the permeability of the strata in the zone adjacent to the fault. This in some cases permits groundwater to penetrate to greater depths than would normally be possible. However, the presence of faults does not automatically increase groundwater flow. For instance, in other locations, the aquifer horizons are disrupted into isolated blocks bounded by faults across which groundwater flow is minimal. This can occur when fault gouge infills the fault plane. In extensively faulted areas, the aquifer horizons may possess little or no outcrop area, so recharge is severely limited and initially promising borehole yields may decline rapidly as aquifer storage is depleted with pumping.

8.1.4.4 *Folding*

The influence of folding on hydrogeological conditions is best known in the Coal Measures Group of the East Midlands Coalfield where it tends to open joints in anticlinal areas, permitting water to infiltrate and migrate down bedding planes to accumulate in synclinal areas. Mine workings sited in synclinal areas tend to be far wetter than those sited on anticlines (Downing et al., 1970; Gray et al., 1969). Elsewhere the effects of folding are often complex and more difficult to predict.

8.1.4.5 *Lateral extent of aquifers*

Many sandstones and some limestones, particularly those of Westphalian age, are local developments and not laterally persistent. In some cases thick localised sandstones have an extensive outcrop area through which recharge can occur but thin rapidly down dip and yield little or no groundwater at depth. Where the aquifer horizon has an outcrop area of limited extent, recharge may be insufficient to sustain initially high yields, which decline with time as storage is depleted.

8.1.4.6 *Effective aquifer thickness*

The complex alternation of argillaceous, arenaceous and limestone strata often makes it difficult to determine the effective aquifer thickness at any given location. Available geological logs are frequently too inexact to allow the precise identification of particular water bearing horizons which contribute to the yield. Even where detailed geological logs provide the thickness of individual sandstone, grit or limestone horizons there is rarely sufficient information to identify which of these horizons are contributing to the total water inflow into the borehole. Hydraulic conductivity values calculated from the transmissivity and geological data are therefore likely to be misleading as the effective aquifer thickness in most boreholes is considerably less than the water filled borehole depth.

8.2 SOUTH-WEST ENGLAND

8.2.1 Geology and stratigraphy

8.2.1.1 *Extent of aquifer group, stratigraphy and lithology*

The outcrop of Carboniferous strata in south-west England occupies a roughly rectangular area extending from Croyde Bay and Boscastle on the western margin, to Wiveliscombe and the Exeter area in the east (Figure 8.6). A number of mostly small outliers occur to the south, particularly in the area between the Bodmin Moor and Dartmoor igneous intrusions and on the south-eastern flank of Dartmoor. A large inlier, surrounded by Permo-Triassic strata, occurs to the north-east of Clyst in the Exe valley. A long, narrow buried valley (the Crediton Trough), filled with Permo-Triassic strata, extends westward into the Carboniferous outcrop, for about 35 km from the vicinity of Clyst.

Dinantian strata outcrop along much of the northern margin, with discontinuous outcrop and numerous small inliers along the southern margin. The rest of the outcrop area is occupied by rocks of Silesian age commonly referred to in this area as Culm. The southern margin of the outcrop in particular has undergone a highly complex structural history of folding and faulting which has fragmented the Dinantian outcrop. The synclinal form of the Culm exposes Westphalian strata from Tiverton to Bude, flanked to the north and south by older Namurian members.

Dinantian

In Devon and Cornwall the Dinantian facies are basinal with non-calcareous mudstones and cherts with a few local limestones. The Buckator Formation, which is limited to Cornwall, comprises mudstones metamorphosed to slates, with thin lenticular limestones. The Westleigh Limestone, which is limited to north-east Devon, comprises mudstones with thick limestone calcarenite beds, interpreted as turbiditic in origin, composed of shell and limestone grains cemented by calcite. The Dinantian stratigraphic succession (including formation names) for the Culm Basin area is shown in Table 8.3.

Silesian

The Culm Measures as a whole are of Silesian age and are subdivided into a lower Crackington Formation, largely of Namurian age, and an upper Bude Formation, of Westphalian age. The former comprises shales with subordinate thin turbiditic sandstones and siltstones. At the base in the Exeter and Newton Abbot districts the shales contain sparse thin sandstones. The Bude Formation comprises thick-bedded massive sandstones with subordinate siltstones and mudstones and only a few turbidites. It passes laterally toward the west into the more marginal marine facies of the Bideford Formation. Correlations for the Namurian and Westphalian sequences exposed in the two limbs of the synclinorium are shown in Figure 8.7.

8.2.1.2 *Structural geology*

The Silesian and Dinantian sediments lie in a broad synclinorium structure trending east-west, flanked to the north and south by Devonian strata.

8.2.2 Hydrogeology

8.2.2.1 *Introduction*

Dinantian

Over much of the area, Dinantian strata are only likely to constitute a marginal aquifer, being predominantly composed of mudstones with thin discontinuous limestones. The mudstones act as aquicludes between the water-bearing limestones. The latter are generally well cemented and possess very limited primary porosity or permeability. Groundwater is stored within and moves through fractures in the limestones. These fractures may have been to some

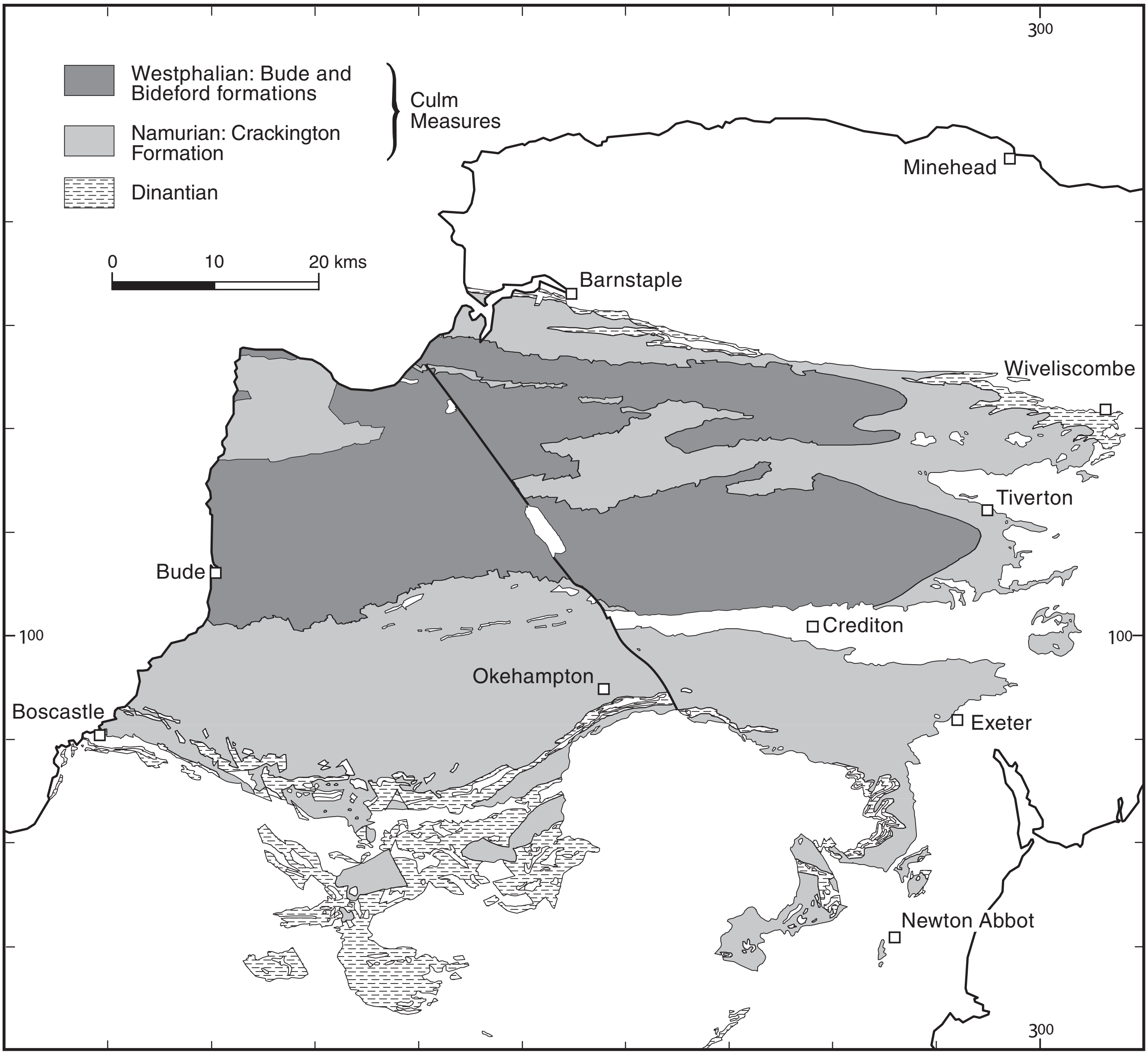
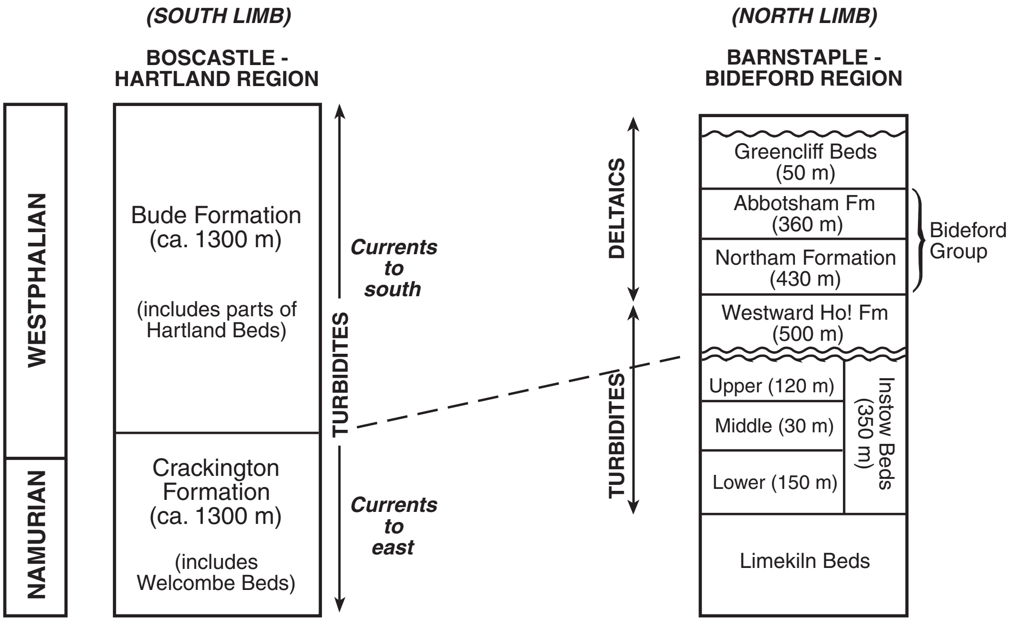


Figure 8.6 Distribution of Carboniferous outcrops in south-west England.

Figure 8.7 Correlations for Namurian and Westphalian sequences in south-west England (after Leeder 1992).



degree enlarged by solution. The yield of a borehole in these strata is dependent not only on penetrating a limestone horizon but also on the degree of fracturing and solution enhancement of the limestone. In view of the discontinuous nature of the limestones, limited outcrop areas (and hence limited recharge), storage is likely to be depleted with pumping even at fairly modest rates, leading to declining yields in the long term.

Silesian (Culm)

These strata comprise a multilayered aquifer system with the impermeable mudstones and shales acting as aquicludes between sandstone horizons which act as separate aquifer units. The sandstones are however generally well cemented and possess little primary porosity or permeability and groundwater storage. Again, groundwater storage and movement is mainly dependent on the presence of fractures. A statistical analysis of records for boreholes penetrating the Culm showed that fractures appeared to diminish in frequency with depth and that boreholes constructed to depths greater than 50 m rarely obtained any increase in yield. Average borehole depth was of the order of only 40 m (Monkhouse, 1985).

8.2.2.2 *Core data*

There are no known values of porosity or permeability derived from the laboratory analysis of rock core or outcrop samples for Dinantian or Silesian strata in this area.

8.2.2.3 *Pumping test results*

Dinantian

TRANSMISSIVITY AND STORAGE COEFFICIENT

Transmissivity values are available for only nine sites in the area under consideration, of which five are scattered across the southern outcrop and four clustered together at the western extremity of the northern outcrop. Given the marked differences between the lithologies of the two outcrops and the geographical distribution of the sites, it is not considered that any statistical analysis of the data will provide any helpful conclusion and could in fact be misleading.

Transmissivities for sites on the southern outcrop range from 1 to about 45 m^2/d with one extreme value of over 260 m^2/d. There is a single storage coefficient of 0.01 which is indicative of unconfined conditions, but it is not possible to assess if this is representative. Transmissivity values from sites on the northern outcrop are quite variable, ranging from 2.6 to 56 m^2/d with one extreme value of about 1000 m^2/d. No storage coefficients are available for sites on the northern outcrop.

SPECIFIC CAPACITY

Specific capacities are only available for the sites referred to above. In view of the limited number of values and their distribution, a statistical analysis has not been carried out. The specific capacities for the southern outcrop area vary widely ranging from 1.5 to over 270 $m^3/d/m$, those for sites on the northern outcrop have a much smaller range of only 6.3 to 13 $m^3/d/m$.

Silesian

TRANSMISSIVITY AND STORAGE COEFFICIENT

Sites for which transmissivity values are available are concentrated in the south and east of the outcrop area. Fifty three transmissivity values are available for the Culm as a whole, of which 33 sites are attributable to either the Bude or Crackington formations, the remainder only being identified generically as Culm Measures.

For the Culm Measures as a whole, transmissivity generally ranges from 0.2 to 245 m^2/d, the interquartile range is from 1.3 to 6.2 m^2/d and the arithmetic mean, geometric mean and median values are 11, 3.4 and 2.8 m^2/d respectively. There is no linear relationship between transmissivity and specific capacity (Figure 8.8). Storage coefficients range from 10^{-3} to 0.8 indicating generally unconfined conditions; the higher values are probably spurious.

There are a total of 26 Crackington Formation sites of which only two have been tested twice. Transmissivities range from 0.2 to 93 m^2/d, all but three of the values being below 10 m^2/d. This is reflected in the interquartile range of only 1 to 6 m^2/d and arithmetic mean, geometric mean and median of 7.7, 2.8 and 3.0 m^2/d respectively (Figure 8.9).

Only seven sites are available for the Bude Formation so no statistical analysis was conducted. Transmissivities range from 1 to about 23 m^2/d with a mean of about 10 m^2/d. Two of these sites were tested twice and results from each pair of tests gave very similar transmissivity results despite being pumped at very different rates.

Davey (1981) estimated transmissivity values from basic pumping test data for 30 boreholes which penetrated the Culm Measures in central and east Devon for a standard pumping period of 120 minutes. Mean values for unconfined (water table) and confined conditions were 8 and 19 m^2/d respectively for the Crackington Formation and 16 and 18 m^2/d for those penetrating the Bude Formation. Davey considered that the most probable cause of this relationship was that under water table conditions, where the shallowest strata are of greater importance, the fractures in the massive hard sandstones of the Bude Formation would remain open whereas those in the more argillaceous Crackington Formation would be less permeable due to the effects of weathering. The hydraulic properties of the two formations would however be more similar at depth under confined conditions.

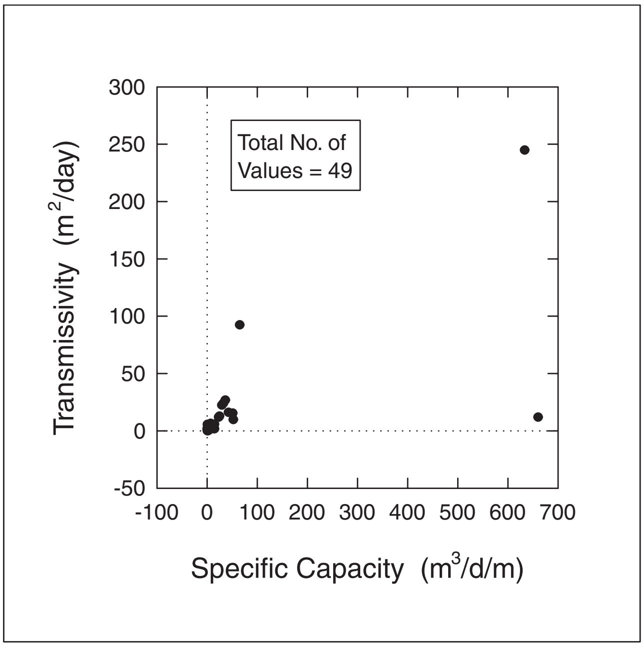


Figure 8.8 Correlation between specific capacity and transmissivity for the Culm Measures of south-west England.

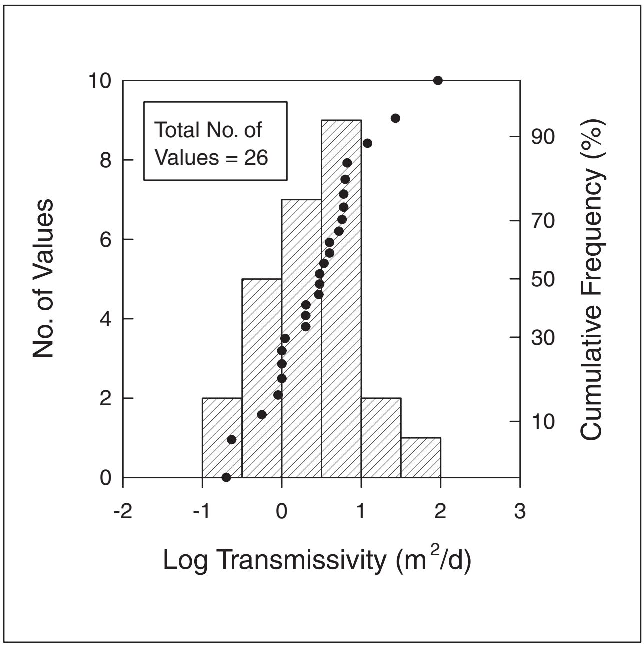


Figure 8.9 Distribution of transmissivity data from pumping tests in the Crackington Formation of south-west England.

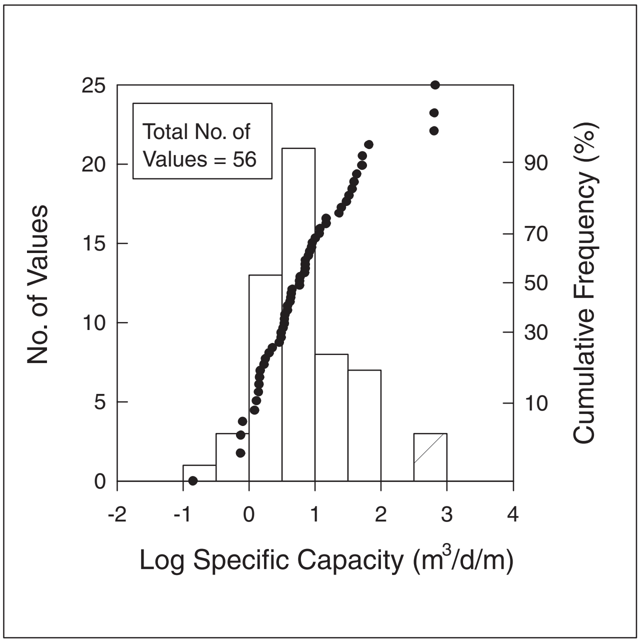


Figure 8.10 Distribution of specific capacities from pumping tests in the Culm Measures of south-west England.

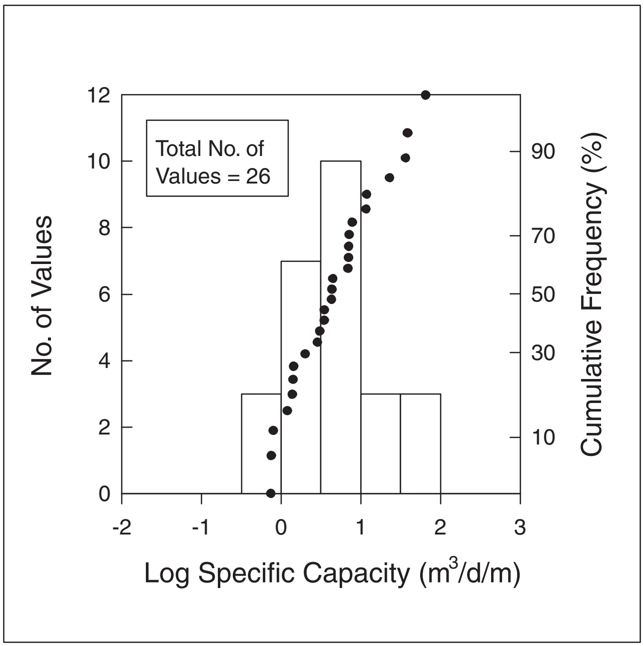


Figure 8.11 Distribution of specific capacity data from pumping tests in the Crackington Formation of south-west England.

SPECIFIC CAPACITY

Fifty six specific capacity values are available. Of the total, 30 sites are attributable to either the Bude Formation (seven sites) or Crackington Formation (23 sites), the remainder only being identified as Culm Measures.

For the Culm Measures as a whole, specific capacities range between 0.14 and about 65 m^3/d/m, with two extreme values of 633 and 660 m^3/d/m obtained for sites at Lew Mill Farm [SX 46750 86240] and Trebullom [SX 23230 82550] respectively. Duplicate values are usually consistent. The interquartile range is 2 to 15 m^3/d/m, with arithmetic mean, geometric mean and median values of about 45, 7 and 6 m^3/d/m respectively (Figure 8.10). A tabulation of specific capacity values for the Culm Measures of central and east Devon provided by Davey (1981) ranged from 0.3 to 25 m^3/d/m.

Borehole depths in the Crackington Formation only rarely exceed 60 m. There are 16 values of specific capacity, which range from 0.7 to 65 m^3/d/m with an interquartile range of about 1.4 to 9 m^3/d/m, an arithmetic mean, geometric mean and a median of about 10, 5 and 4 m^3/d/m respectively (Figure 8.11). Yields and drawdowns are both very variable, ranging from 2.5 to 95 m^3/d and 1.4 to over 35 m respectively.

For the small Bude Formation dataset, specific capacities range from 1.7 to 52 m^3/d/m with an interquartile range of about 4 to 20 m^3/d/m. Two of the boreholes were tested at two markedly different discharge rates but gave similar specific capacity values for each pair of tests.

8.2.2.4 *Yield data*

Dinantian

Yields from five boreholes of about 125 mm diameter located on or near the southern outcrop, (where mudstones with thin discontinuous limestone lithologies are prevalent), range from 30 to 58 m^3/d (with one exceptional yield of 90 m^3/d), for highly variable amounts of drawdown. The Bampton Limestone Series, at the top of the sequence, yields small amounts of very iron rich water (Institute of Geological Sciences, 1982a).

The largest, most sustainable yields are likely to be obtainable from the thicker limestone horizons such as the Westleigh Limestone of north-east Devon. A group of four boreholes, of 150 to 200 mm diameter, located at the extreme eastern end of the northern outcrop recorded yields ranging from 60 to 830 m^3/d, for drawdowns ranging from 4.4 to 45 m, with one exceptional yield of over 1600 m^3/d. Three of the four boreholes were recorded as being drilled in Westleigh Limestone illustrating the high degree of variability in these strata.

Silesian (Culm)

Large quantities of groundwater are not generally obtainable from these strata, the largest recorded being 150 m^3/d from the Crackington Formation and 370 m^3/d from the Bude Formation (Monkhouse, 1985). Yields of this magnitude, whilst generally inadequate for public supply sources, are of great importance for meeting local domestic and agricultural requirements. Sherrell (1962) considered that the oxidation of iron taken into solution from the shales was likely to cause a reduction in yield due to the deposition of precipitates in the water bearing fractures. No specific examples were provided however and the possibility that declining yields may have been a response to the depletion of storage by pumping does not seem to have been considered.

8.3 SOUTH WALES, THE FOREST OF DEAN AND BRISTOL AREA

8.3.1 Geology and stratigraphy

8.3.1.1 *Extent of aquifer group, stratigraphy and lithology*

The Carboniferous in south Wales extends from St Brides Bay, Pembrokeshire in the west, across Cardigan Bay, to the Abergavenny/Pontypool area in the east. In the west the outcrop is comparatively narrow but widens rapidly eastward. The Coal Measures occupy the centre of the outcrop with narrower Millstone Grit and Carboniferous Limestone outcrops fringing the northern, eastern and southern margins. The Forest of Dean outcrop consists of an outlier of Carboniferous rocks located between the Rivers Severn and Wye, the Carboniferous Limestone fringing the outcrop and Silesian strata in the core. To the east of the River Severn there are numerous smaller outcrops of Carboniferous Limestone, the largest forming the Mendips. Several small coalfields are also located to the north and south of Bristol. The distribution is shown in Figure 8.12.

To the east of Carmarthen Bay, the outcrop is drained predominantly towards the south by rivers such as the Loughor, Neath and Taff and their tributaries. Most of these rivers rise on pre-Carboniferous strata to the north of the outcrop area and their valleys are commonly deeply incised and steep sided.

The eastern section of the south Wales Carboniferous outcrop includes the South Wales Coalfield on which many of the larger centres of population in Wales are located. Major urban and industrial development in the area from the eighteenth century onward was dependent on the presence of coal in association with water resources and other raw materials such as mineral ores and clays suitable for brick making.

Dinantian

The stratigraphy of the Carboniferous Limestone in south Wales and the Mendips has previously been described in detail in Allen et al. (1997) and will not therefore be considered further here. In the Bristol and Mendips area the Dinantian rocks are mainly carbonates, although the lowermost beds, the Lower Limestone Shale, are dominantly mudstone. Sandstone beds are present in the upper part of the Dinantian succession to the north of Bristol, occurring interbedded with limestones. Stratigraphic correlations for the south Wales and Bristol areas are shown on Table 8.3.

Namurian

The Millstone Grit in south Wales consists of cyclic sequences of shales and sandstones with subordinate residual soil horizons and coals. The stratigraphy is dominated by argillaceous deposits, particularly on the southern limb of the anticline where the sequence is thickest. The main sandstones are found on the northern and eastern outcrops where the succession is characterised by an alternation of sandstones with marine shales (Ramsbottom et al., 1978). The strata in south Wales commonly show rapid lateral changes from silty mudstone to laterally impersistent, coarse-grained, cross-bedded sandstone and conglomerate. The basal grit is probably the best developed sandstone, attaining a thickness of 120 m on the northern outcrop in the vicinity of the Loughor and Tawe valleys. On the northern outcrop, to the north-west of Merthyr Tydfil, sandstones constitute 150 m of the Millstone Grit sequence but this

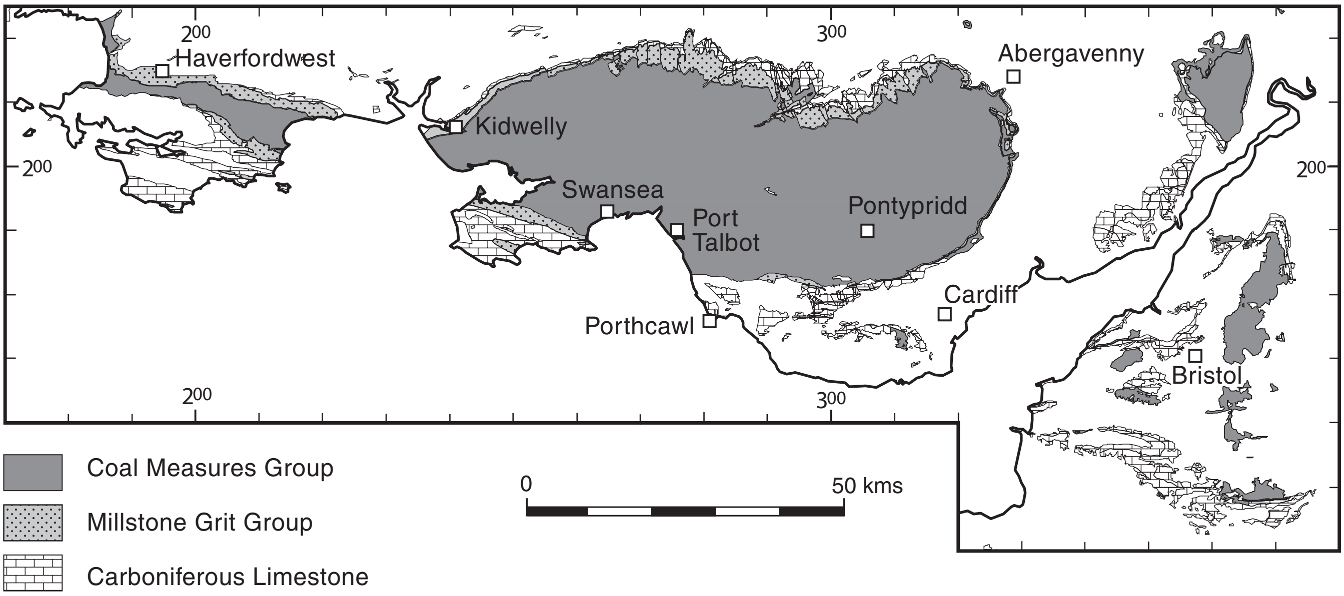


Figure 8.12 Distribution of Carboniferous outcrops in south Wales, the Forest of Dean and the Bristol area.

reduces to about 100 m on the south-western part of the southern outcrop and 20 m at most in the east (Holliday, 1986).

In the Bristol area, sandstones of the Quartzitic Sandstone Group predominate. The sandstones thin to the south-east and west of Bristol but maintain a thickness of the order of 300 m to the north.

Westphalian

Westphalian stratigraphic subdivisions are based upon laterally extensive marine bands and coal seams which in general have little hydrogeological significance. The main stratigraphic sub-divisions, together with a schematic lithological log, are shown in Figure 8.13. The distribution of Westphalian strata in the South Wales Coalfield area together with main structures is shown in Figure 8.14.

The Lower and Middle Coal Measures strata are predominantly argillaceous in nature. Thick sandstones of significant lateral extent are rare and represent localised deltaic distributary channels. Individual sandstones can attain a thickness of 50 m but total thickness of the sandstones is not significant and invariably less than 100 m. The Farewell Rock, a flaggy sandstone formerly considered to constitute the base of the Coal Measures, represents a southward progradation of a relatively persistent delta lobe in the north-east of the basin (Kelling and Collinson, 1992). Argillaceous deposits together with thick extensive coals, residual soil horizons and ironstone bands predominate in the Westphalian B stage.

Mudstones continue to dominate in the lower part of the Westphalian C stage but the first lithic Pennant-type fluvial sandstones occur during this period in mid-Glamorgan and are indicative of deposition from the south. The upper part of the stage, and much of the succeeding Westphalian D stage, is characterised by massive fluviatile lithic sandstones (the Pennant Sandstones) with subordinate argillaceous horizons and a few thick coals. These Pennant Sandstones, sometimes referred to as the Pennant Measures, are often considered to be synonymous with the Upper Coal Measures in south Wales. The Pennant Measures typically comprise bluish grey, weathered brown, thick massive or cross-bedded feldspathic and micaceous, fine- to coarse-grained and locally pebbly sandstones. In south Wales the sandstones tend to be confined to the lower part, and there is an upward increase in the proportion of argillaceous beds and number of coal seams. Fluvial channel facies, consisting of conglomerates, medium to coarse grained sandstones and local finer-grained units, make up over 80% of the Rhondda, Brithdir and Hughes beds (Figure 8.13) (Jones and Hartley, 1993). Fine grained sandstone, siltstone and mudstone flood plain facies with occasional fluvial channel deposits are characteristic of the uppermost Grovesend and Swansea beds, whilst the Llynfi Beds are composed of fluvial channel deposits in the centre of deposition, thinning and being replaced by flood plain deposits towards the basin margins (Jones and Hartley, 1993).

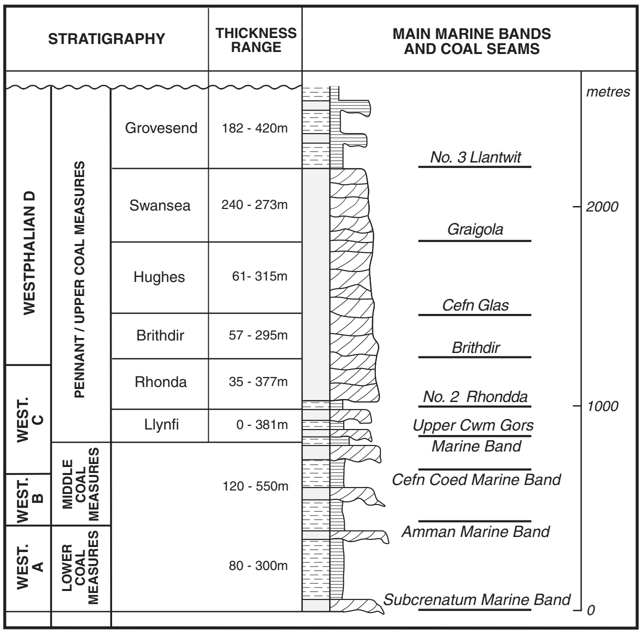


Figure 8.13 Stratigraphic subdivisions and schematic lithological log for the Westphalian of south Wales.

The Upper Coal Measures of the Forest of Dean consist of a basal unit of shales, mudstones, grits and conglomerate (the Trenchard Group), overlain by about 500 m of massive sandstones and subordinate shales (the Pennant Group). The uppermost Supra Pennant Group consists of a lower shaly unit (about 90 m thick), with an upper unit of thick sandstones with subordinate coals.

In the Bristol area argillaceous strata predominate, with a thicker sequence of sandstones constituting the upper part of Westphalian C (Downend Formation) and lower section of Westphalian D (Mangotsfield Formation).

8.3.1.2 *Regional structure*

The Carboniferous strata of south Wales are folded into a broad east-west trending asymmetrical synclinorium, with subsidiary folds, such as the Pontypridd Anticline and Gelligaer Syncline, (also trending generally east–west), superimposed on this structure (Figure 8.14). The steepest regional dips occur on the eastern and southern margins of the syncline. The detailed structure is complex due to extensive faulting and the presence of small scale folding associated with compressional structures (Ineson, 1967).

8.3.2 Hydrogeology

8.3.2.1 *Introduction*

A large portion of the area considered in this section is covered by the Hydrogeological Map of South Wales (British Geological Survey, 1986) which provides information on the hydrogeological properties and groundwater chemistry of the various strata underlying the area.

Dinantian

The hydrogeology and aquifer properties of the Carboniferous Limestone in south Wales and the Mendips has previously been described in detail in Allen et al. (1997). No additional information is available for the other smaller outcrop areas to the east of the River Severn.

Namurian

The Millstone Grit is not widely utilised as an aquifer in south Wales. Millstone Grit sandstones are invariably well cemented and hard with very low primary porosity and intergranular permeability. Groundwater storage and movement occurs predominantly within and through fractures. Borehole yields are commonly of the order of only 250 m^3/d but can attain 865 to 1030 m^3/d, particularly where associated with faulting. Springs capable of providing similar yields occur where shales are faulted against sandstones (British Geological Survey, 1986).

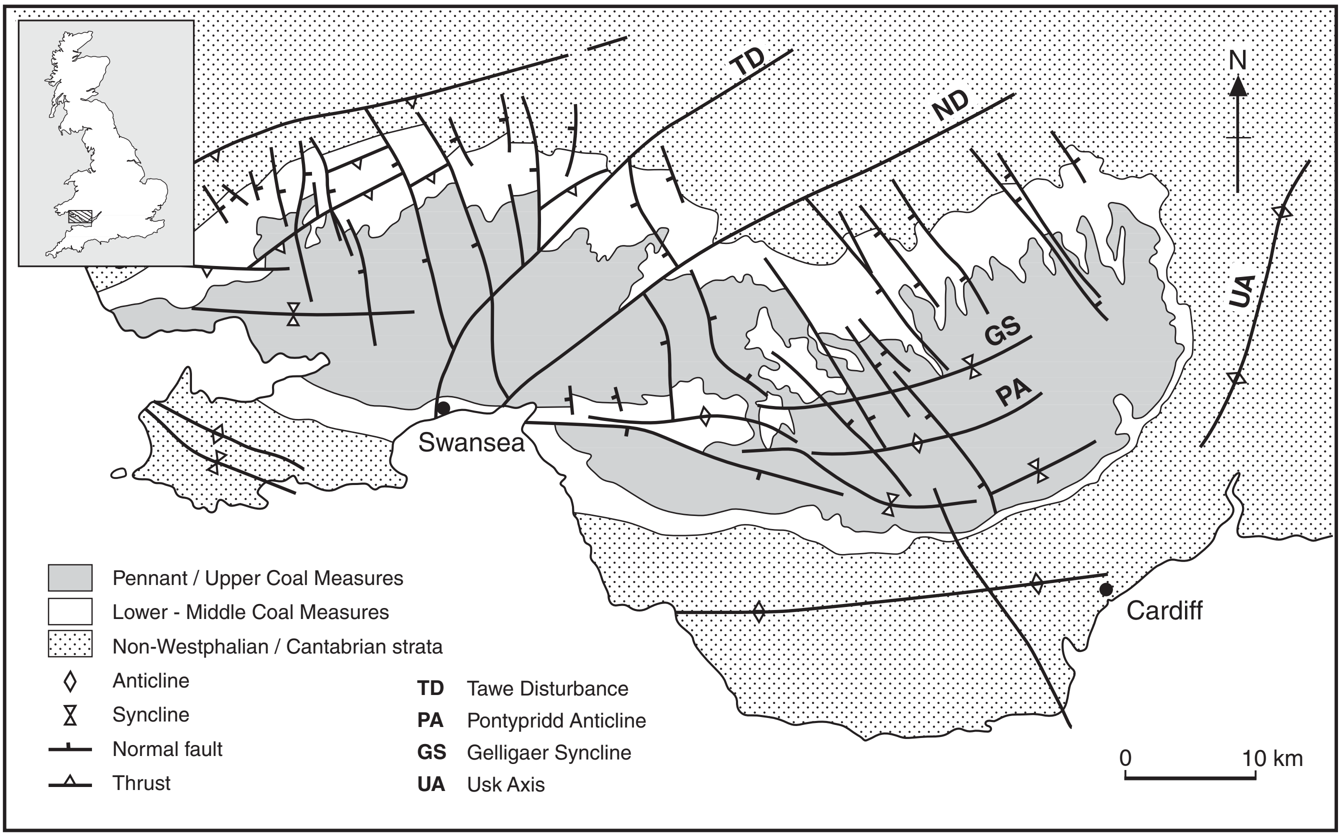


Figure 8.14 Distribution of Westphalian outcrop and main structures in the South Wales Coalfield.

To the east of the River Severn, Millstone Grit outcrops are very limited in size and do not constitute an aquifer of any importance (Richardson, 1930).

Westphalian

Coal Measures sandstones are very well cemented, extremely hard and dense and in consequence possess very little primary porosity or intergranular permeability. Sandstone permeability is directly related to the distribution and size of fractures present in the sandstone horizons. Under natural conditions they act as individual aquifers separated by intervening impermeable argillaceous horizons and constitute a complex multi-layered aquifer system. This condition has however largely been disrupted by mining subsidence which has created hydraulic continuity between water bearing layers and in some locations between aquifer horizons and mine workings. Fractures can range up to several centimetres in aperture at outcrop and at shallow depths (Holliday, 1986).

The South Wales Coalfield has traditionally been regarded as one of the wettest in the United Kingdom, pumping an average of 8 m^3 of water per ton of mined coal compared with only 2 m^3/ton for mines in England and Wales as a whole (Rhodda et al., 1976). Prior to widespread closures in the late 1970s, about 15% of mines pumped over 4320 m^3/d with 40% pumping less than 1730 m^3/d and 30% less than 340 m^3/d (Rae, 1978a). The structure of the Coal Measures appears to control groundwater flow rates, which tend to be greatest from mines working in synclinal structures. In addition deeper mine workings were generally drier than shallow workings probably due to a reduction in permeability with increasing thickness of overburden and the closure of fractures. Under such circumstances, any water entering the workings was likely to be derived from the Upper Coal Measures moving downward via faults (Holliday, 1986). The permeability of Upper Coal Measures/Pennant Measures sandstones was also generally higher than the sandstones of the Lower and Middle Coal Measures, due to the effects of mining subsidence. Subsidence produced irregular zones of tensional and compressional strains resulting in increased fracturing (Holliday, 1986). Flows in such zones can exceed 500 m^3/d, a value greatly in excess of the intergranular permeability of about 3×10^{-6} m/d (10^{-2} mD) (Mather et al., 1969). A detailed study of the Aberfan area (Mather et al., 1969) indicated that mining subsidence caused areas of tensional strain. In these areas, there was increased aquifer recharge due to the development of surface fractures, and increased storage capacity and transmissivity of the sandstones due to the enlargement of pre-existing subsurface fractures.

In the Forest of Dean it became necessary to construct low gradient drainage adits out from valley floors as coal mining extended to deeper levels during the 18th century (Aldous et al., 1986). This general lowering of water levels dried many wells previously used for supply in the area. As mining depths further increased it became necessary to pump the workings. An indication of the quantity of recharge entering the deep workings was provided by Richardson (1930). At that time an average of over 40 000 m^3/d was pumped, in addition to an unknown quantity drained from workings via adits. Of the total pumped, two-thirds was from only two collieries. When mining ceased, the deeper levels flooded but many of the drainage adits continue to function today.

8.3.2.2 *Availability of aquifer properties data*

The amount of aquifer properties data for the Silesian rocks in the south Wales area is very limited. Intergranular porosity and permeability data from the laboratory analysis of

Middle Coal Measures cores were quoted by Holliday (1986). BGS archives also contain measurements for Upper Coal Measures samples for one borehole and a single outcrop sample.

Information derived from aquifer testing is also sparse with values from only single sites in the Lower and Middle Coal Measures and from nine boreholes in the Upper Coal Measures. Being too sparse for use in statistical analysis, the available information is discussed below but parameter values quoted are not to be regarded as representative, especially as no data are available for the Silesian strata in the Forest of Dean or Bristol areas.

8.3.2.3 *Core data*

Namurian

There are no known values of porosity or permeability derived from the laboratory analysis of Namurian rock core or outcrop samples.

Westphalian

Holliday (1986) provided details of laboratory measurements on samples obtained from a sandstone above the Big Vein in the Middle Coal Measures at Cynheidre [SN 494 075]. Six samples were taken from depths between 483 and 518 m below ground level; intergranular permeabilities were low, ranging from 5.8×10^{-6} to 1.1×10^{-4} m/d (0.017 to 0.28 mD) with arithmetic mean and median values of 1.1×10^{-3} and 1.0×10^{-3} m/d (2.4 and 2.3 mD). Porosity values did not exceed 2.4%.

BGS archives also contain data for a single Upper Coal Measures outcrop sample located at [SO 6443 1629], from which subsamples at various horizontal and vertical orientations were obtained. Horizontal permeabilities were all about 4.2×10^{-4} m/d (1 mD) but vertical values ranged from 4×10^{-4} to over 0.055 m/d (1 to over 100 mD). Porosities ranged from 11.3 to 13.6%. Analysis of a total of 21 core samples from Betws No. 4 Borehole [SN 6530 0710] from depths of between 900 and 932 m below surface, provided porosity values of between 1.7 and 4.8%. Permeability values ranged from 0.12 to 1.3×10^{-5} m/d (1×10^{-2} to 7494 mD).

8.3.2.4 *Pumping test results*

Namurian

TRANMISSIVITY AND STORAGE COEFFICIENT

The only transmissivity value available for the Millstone Grit, is for the test discussed briefly below, from which a value of 43 m^2/d was calculated.

SPECIFIC CAPACITY

Only a single aquifer test is available on the database for the Millstone Grit of south Wales. The borehole, located at Rhymney Bridge [SO 1046 0996], which penetrated to a depth of 118 m was pumped at a rate of 1329 m^3/d and gave a specific capacity value of only 21 m^3/d/m.

Westphalian

TRANMISSIVITY AND STORAGE COEFFICIENT

Ineson (1953), using analyses of limited data derived from a variety of sources, concluded that transmissivity values for the Coal Measures ranged from 0.15 to 225 m^2/d. The lower values were associated with smaller diameter boreholes. The larger values are likely to be unrealistically high, as they were derived from non-steady state data from the pumping of abandoned mine workings and therefore reflect the large volumes of storage present within the old workings.

The only transmissivity and storage values specifically for the Lower Coal Measures are from a test on a production borehole with four observation boreholes, (of which two were constructed as production boreholes), at Pengarnddu, Merthyr Tydfil [SO 0810 0860] (W Davies, personal communication). Geological and hydrogeological conditions at the site are complex with marked lithological variations over very short distances and the presence of barrier boundaries, probably due to faulting. It is also probable that mining activities in the vicinity influence local hydrogeology. Despite the presence of such complex conditions, the transmissivity values obtained, (with the omission of one observation borehole which was distinctly anomalous), were within a narrow range (3 to 15 m^2/d). Storage coefficients from three of the observation boreholes indicated confined conditions, ranging from 1×10^{-4} to 4×10^{-5}.

Similarly the only transmissivity for the Middle Coal Measures is from a test carried out at Aberdare Golf Club [SO 0134 0304] which provided a value of 11 m^2/d.

Of the ten transmissivity values available for boreholes penetrating the Upper Coal Measures, seven fall within the range of 30 to 65 m^2/d, with extreme values of 0.24 and 350 m^2/d. The maximum was from the first three hours of pumping of an observation borehole at Felindre [ST 6401 0370] where the production borehole (only 35 m away), had a transmissivity of 45 m^2/d. The same observation borehole provided the only storage coefficient (0.002) available for the Upper Coal Measures in the south Wales area. It should be stressed that although these values may be indicative of the magnitude of values that may be anticipated, they cannot be regarded as representative of the Upper Coal Measures in the area.

SPECIFIC CAPACITY

The only specific capacity value for the Middle Coal Measures was calculated from the test on the Aberdare Golf Club Borehole; this gave a value of 9 m^3/d/m. The test on the production borehole penetrating the Lower Coal Measures at Perngarnuddu, Merthyr Tydfil gave a value of about 14 m^3/d/m.

Specific capacity values for eight tests on boreholes penetrating the Upper Coal Measures (Pennant Measures) range over almost two orders of magnitude (2.6 to 250 m^3/d/m). At Caerphilly two boreholes of similar depth (96 and 91.4 m) in close proximity [ST 1429 8658 and 1418 8656] gave specific capacities of 27 and 11 m^3/d/m respectively, indicating the presence of fairly uniform local aquifer conditions; however, barrier boundaries associated with faulting were noted. Two boreholes, both 40 m deep, at East Glamorgan Hospital [ST 08130 85950 and ST 08050 85900], were pumped at rates of 288 and 192 m^3/d respectively for drawdowns of only 1.3 and 2 m; this gave specific capacities of 222 and 96 m^3/d/m, although transmissivities for both were 45 m^2/d, again indicating locally uniform conditions.

8.3.2.5 *Yield data*

Westphalian

Borehole yields from the Lower and Middle Coal Measures only rarely exceed 90 m^3/d (1 l/s) although exceptionally a yield of 648 m^3/d was obtained from a 115 m deep 250 mm diameter borehole at Rhymney [SO 110 082]. Higher yields are obtainable from the Upper Coal Measures, particularly where these strata are over 60 m thick and beneath valley side sites, but even under such conditions yields do not often exceed 430 m^3/d (British Geological Survey, 1986). Mine shafts and adits can yield over 8650 m^3/d. Recorded inrushes of water through the floor or roof of mine workings have ranged up to 21 600 m^3/d but although initial quantities can be large, flow rates tended to reduce asymptotically. Where initial yields were small the reduction in flow was often negligible (Ineson, 1967). Inrushes tended to occur most commonly in the eastern part of the coalfield, where the intervals between the lowest workings and the underlying Coal Measures or Millstone Grit sandstones were least (British Geological Survey, 1986). Higher yields may also be obtainable from boreholes which penetrate old flooded mine workings, but this may be at the cost of quality.

8.4 NORTH WALES

8.4.1 Geology and stratigraphy

8.4.1.1 *Extent of aquifer group, stratigraphy and lithology*

The distribution of Carboniferous outcrops in north Wales is shown in Figure 8.15.

The Carboniferous Limestones form two approximately parallel outcrops. One trends south-eastwards from Great Ormes Head then southwards through Denbigh to Llanelidan, the series dipping eastwards into the Vale of Clwyd syncline to reappear in isolated narrow outcrops along the Vale of Clwyd. Coal Measures rocks occupy a broad outcrop across the northern part of the Vale around St Asaph. The other Carboniferous Limestone outcrop runs south-east from the coast near Prestatyn before swinging southwards from Halkyn to Llandegla, the limestones dipping eastwards off the Clwydian Range with minor folds such as that in Halkyn Mountain. The Llanelidan Fault causes an eastward displacement of this outcrop to Minera, from where the limestone has a sinuous southerly course, and an easterly dip, through Llangollen to end abruptly in Llanymynech Hill. Heights along the easterly outcrop rarely fall below 200 m, while the tracts of limestone west of the Vale of Clwyd are generally below 180 m. These limestone outcrops are flanked to the east by Millstone Grit and Coal Measures outcrops.

Three sizeable outcrops of Carboniferous Limestone occur in Anglesey, with a maximum altitude of 150 m in the eastern corner of the island.

Dinantian

The Dinantian in north Wales is largely restricted to the uppermost Asbian and Brigantian stages (George et al., 1976). A general classification of the Carboniferous Limestone in north Wales was given by Morton (1897) and quoted in Appleton (1989) (Table 8.4).

Table 8.4 Dinantian stratigraphic succession in north Wales.

Stratigraphic succession	Thickness
Sandy Limestone or Black Limestone of north Clwyd	160 m
Upper Grey Limestone	250 m
Middle White Limestone	500 m
Lower Brown Limestone	300 m
Basement Beds	100 m

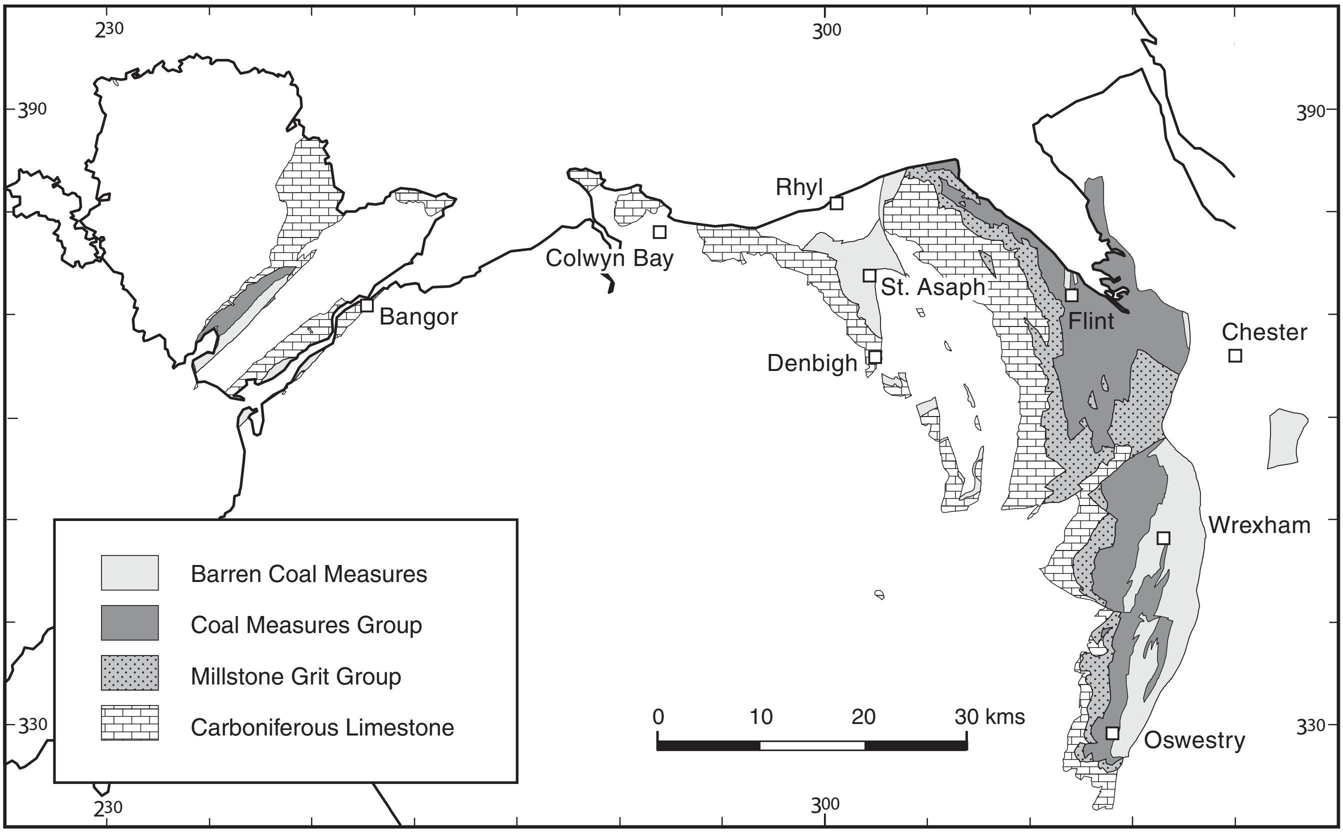


Figure 8.15 Distribution of Carboniferous outcrops in north Wales.

The Basement Beds (Holkerian or Asbian) overlie the Silurian rocks unconformably. They are markedly different from the rest of the series and consist of sandstones, conglomerates, shales, impure calcite mudstones, calcareous sandstones and occasional fine-grained limestones, which are typically red, purple or green-mottled. The overlying strata comprise dominantly fossiliferous limestones with variable quantities of mud and sand. The Lower Brown Limestone is usually thinly bedded with frequent shale partings. It reaches a maximum thickness of 300 m (at Llandegla). The overlying Middle White Limestone contains thick massive beds, particularly in the lower part of the sequence, and forms conspicuous outcrop features. It reaches a maximum thickness of 500 m in north-east Clwyd. The Upper Grey Limestone comprises a series of dark, generally thinly bedded fossiliferous limestones containing thick shale beds. The unit reaches a thickness of more than 250 m at Llandegla. The uppermost Dinantian strata include cherty limestones passing laterally towards north-east Wales into a succession of sandstones, sandy limestones and dark bituminous shales. The Sandy Limestone occurs in the south of the eastern outcrop and comprises a variable sequence of sandstones, sandy limestones and shales. Further north the unit passes into the Black Limestone of north-east Clwyd, a thin-bedded, dark, fine grained rock. In Anglesey conglomeratic and sandy diachronous basal beds are succeeded by around 300 m of limestones containing beds of sandstone and shale.

Namurian

The Namurian thickens northward from its southern limit near Oswestry, the sequence becoming more complete and more argillaceous, suggesting increasingly basinal conditions (Ramsbottom, 1974). At the base of the Namurian sequence, the Cefn-y-fedw Sandstone, (decalcified sandstones and quartzites with interbedded shales and cherts), attains a maximum thickness of about 180 m around Ruabon Mountain but dies out northwards. The sandstone thins to about 80 m in the Oswestry area where the shales are virtually absent. The sandstones are overlain by up to 100 m of cherts (Chert Beds) and 120 to 180 m of carbonaceous and siliceous shales with thin coals and interbedded sandstones and quartzites (Holywell Shales). In the north these shales are overlain by up to 90 m of fine grained Gwespyr Sandstone (British Geological Surey, 1989). This sandstone (and probable equivalent, the Aqueduct Grit of the Ruabon area), being Yeodonian, probably represents the outermost extension of the Rough Rock (Kelling and Collinson, 1992).

Westphalian

The Productive Coal Measures at the base of the Westphalian sequence in the area consists of up to 600 m of pyritic shales and clays with impersistent sandstones, thin ironstones and thick coal seams. Sandstones become more common in the south towards Wrexham.

The Productive Coal Measures are overlain by the Barren Measures. At the base are about 335 m of mottled marls (Ruabon Marl), overlain by 160 m of calcareous sandstones (Coed-y-aly Beds) and about 900 m of sandstones and some marls (Erbistock Beds) (British Geological Survey, 1989).

8.4.2 Hydrogeology

8.4.2.1 *Introduction*

The Hydrogeological Map of Clwyd and the Cheshire Basin (British Geological Survey, 1989) includes coverage of Carboniferous strata in the vicinity of the Vale of Clwyd, the margins of the Cheshire Basin and extends westward to Great Ormes Head although little detailed hydrogeological information is available from this source.

Dinantian

Of the numerous areas of Carboniferous Limestone in north Wales the most extensive is that of north-east Clwyd, flanking the Vale of Clwyd, and taking the form of an elevated plateau up to 6 km wide. The area around the Holywell-Halkyn district (15 km south-west of Prestatyn) was the scene of much mining activity from Roman times until recently. Mines were also worked around Abergele and St Asaph on the western side of the Vale of Clwyd.

Information obtained during mining and the driving of drainage tunnels indicate that rock structures largely control the seaward movement of groundwater (Richards, 1959). For example, in the Halkyn area east–west veins may provide some permeability, and north-east cross-course faults assist with northerly flow, with the faults likely to have the higher, though variable, permeability (Richards, 1959). The permeability heterogeneity of the limestone is indicated by different water tables in adjoining blocks of limestone, leading to a so-called ‘chessboard and staircase’ drainage pattern (Smith, 1921).

To mine the lead-zinc deposits economically the lodes were gravity drained, and several schemes involving drainage tunnels were undertaken from 1818. These adits encountered many natural solution caverns. By providing zones of high permeability the drainage tunnels and shafts also substantially affected natural flow systems of the area, and for example adversely affected the main spring of St Winifride’s Well at Holywell (Appleton, 1989). Two of these tunnels, the Milwr Sea Tunnel and Halkyn Deep Level Tunnel, are used for water supply (Campbell and Hains, 1988). Flows from drainage tunnels can be substantial, for example a discharge of 2592 m^3/d was recorded from an adit at Bodelwynddan [SJ 0048 7506].

In Anglesey massive limestones are open along joints, and some caverns have been developed. Bands of shale in the limestones are likely to impede vertical flow (Richards, 1959).

The aquifer properties of the Carboniferous Limestones of north Wales are unknown, but the preceding description suggests that the limestones of the area are just as unpredictable in terms of their permeability distribution as those of south Wales, and storage coefficients are likely to be small.

The limestones have minimal primary porosity or permeability with groundwater storage and movement restricted to solution enlarged fractures. The fractures are not regularly spaced or extensively interconnected. Where present, fracture apertures tend to be large, permitting rapid groundwater movement. Failure to intersect a water-bearing fracture commonly results in a dry or very low yielding borehole. Drilling to obtain a water supply from these strata is highly speculative and few boreholes have been constructed in the area. Discharge from fracture systems occurs at a limited number of large springs with high flow rates, (for example 540 m^3/h from the Dyserth Limestone at Plynnon Asaph [SJ 0752 7506]), but flows vary markedly with time and can decrease by an order of magnitude in dry weather (British Geological Survey, 1989; Campbell and Hains, 1988).

Namurian

These strata act as a multilayered aquifer system, with the impermeable mudstones and shales acting as aquicludes between the sandstone horizons which behave as separate aquifer units. The sandstones are generally well cemented and possess little primary porosity or permeability, and groundwater storage and movement are mainly dependent on the presence of fractures.

Springs occur at the junctions of the jointed sandstones with underlying mudstones and shales; springs at New Hall, near Chirk [SJ 275 388] yielded in excess of 865 m^3/d. Boreholes which fail to intersect water bearing joints or fractures in the sandstones are generally dry or very low yielding. Good yields are occasionally obtained, for example a 45 m deep borehole penetrating the Cefn-y-fedw Sandstone near Oswestry [SJ 2759 3405] produced a yield of almost 2330 m^3/d and was subsequently used for public supply.

Westphalian

These strata also act as a multilayered aquifer system in which the impermeable mudstones and shales act as aquicludes between the sandstone aquifer horizons. Both the argillaceous strata and well cemented sandstones possess minimal primary porosity. Groundwater flow occurs in joints and fractures in the sandstones to depths of up to 250 m below ground level, fracturing often having been enhanced by mining subsidence. Mines penetrating to greater depths were generally dry.

Borehole yields are dependent on the number and size of water bearing joints or fractures penetrated. Yields of 430 m^3/d are not uncommon and a 123 m deep 200 mm diameter borehole at Mold [SJ 2418 6348] yielded over 1390 m^3/d. Initial yields may not be maintained since direct recharge is limited by an extensive cover of low permeability drift. Lateral recharge is also limited due to the fact that aquifer hydraulic continuity is restricted by extensive faulting, splitting the aquifer into isolated blocks. Flooded abandoned mine workings also contain substantial groundwater storage but again yields may not be sustainable in the long term. In addition much of the groundwater in this aquifer is likely to be non-potable.

8.4.2.2 *Core data*

Dinantian

There are no known values of porosity or permeability derived from the laboratory analysis of rock core or outcrop samples.

Namurian

Few samples have been analysed from the Millstone Grit in the area. Outcrop samples from the Cefn-y-fedw Sandstone at Pen-y-foel [SJ 2193 5645] provided porosities of 20% and hydraulic conductivities of 0.4 to 0.7 m/d.

Westphalian

Very few results for the Westphalian rocks in the area are available. Outcrop samples of the Hollin Rock at Wepre Dingle [SJ 2902 6765] provided porosities of about 11% and hydraulic conductivities of less than 6×10^{-4} m/d (Campbell and Hains, 1988). Since these outcrop samples will have been weathered to some degree, both porosities and hydraulic conductivities are likely to be less in unweathered rocks at depth.

8.4.2.3 *Aquifer test data*

Dinantian

Transmissivity values are available for only four sites in the area under consideration, ranging from 0.15 to 1.5 m^2/d. No storage coefficients are recorded. Specific capacity data are only available for six sites in the area. Yields range from 4.7 to a maximum of only 95 m^3/d, commonly for significant drawdowns. Specific capacity values range from 0.13 to 38 m^3/d/m.

Namurian

There is a single aquifer test site on a borehole penetrating the Millstone Grit in this area at Mardy [SJ 2764 3404], towards the southern end of the outcrop. Two tests were carried out on the 260 mm diameter, 45 m deep borehole, of which only the lower 5.5 m was open to the aquifer. Drawdown was only recorded for the higher rate of pumping (6759 m^3/d), which gave a specific capacity of 543 m^3/d/m. No transmissivity or storage coefficients were determined. Given the very large pumping rate, it is unlikely that the values obtained from this test are representative of the Millstone Grit aquifer as a whole in the area.

Westphalian

Specific capacity values are available for seven boreholes penetrating the Westphalian in the area. Of these one is in the Lower Coal Measures, four in the Middle Coal Measures and two in the Upper Coal Measures. Discharge rates at five of the sites ranged between 15 and 170 m^3/d giving specific capacities in the range of 2.5 to 28 m^3/d/m. The boreholes were between 30 and 70 m deep.

The other two boreholes were deeper and were pumped at much higher rates. One borehole at Mold [SJ 1485 2418] penetrated the Middle Coal Measures to a depth of 123 m and was pumped at a rate of almost 1400 m^3/d, providing a specific capacity of 104 m^3/d/m. The other, at Barras Airfield [SJ 368 520] penetrated to a depth of 183 m in the Upper Coal Measures; this was pumped at a rate of 1750 m^3/d and had a specific capacity of 183 m^3/d/m. There is no indication that either of these boreholes encountered disused mine workings but these specific capacities seem high and the lower values are probably more representative of the Westphalian aquifer.

Only one storage coefficient is available, for an Upper Coal Measures site which was pumped at a low rate. The value of 7×10^{-5} is indicative of confined conditions but its validity is suspect, especially since there is no evidence of an observation borehole at the site.

8.5 CENTRAL ENGLAND

8.5.1 Geology and stratigraphy

8.5.1.1 *Extent of aquifer group, stratigraphy and lithology*

The distribution of Carboniferous outcrops in central England is shown in Figure 8.16 and a stratigraphical framework for the Silesian is provided in Table 8.5. This framework is also largely applicable to the Pennines (Section 8.6).

Carboniferous outcrops in central England are dominated by Westphalian rocks with only minor exposures of Dinantian and Namurian strata. Small outcrops of Carboniferous Limestone are located in the west on the margins of the Coalbrookdale Coalfield (to the south-west of Newport and Wellington) and associated with a small Westphalian outcrop as an isolated outlier at Clee Hills. An outcrop of the Millstone Grit and a number of small Carboniferous Limestone outcrops are located on the north-eastern flank of the Leicester Coalfield. The Millstone Grit also outcrops to the north-east of the North Staffordshire Coalfield at Melbourne and Bredon on the Hill, but will be considered as part of

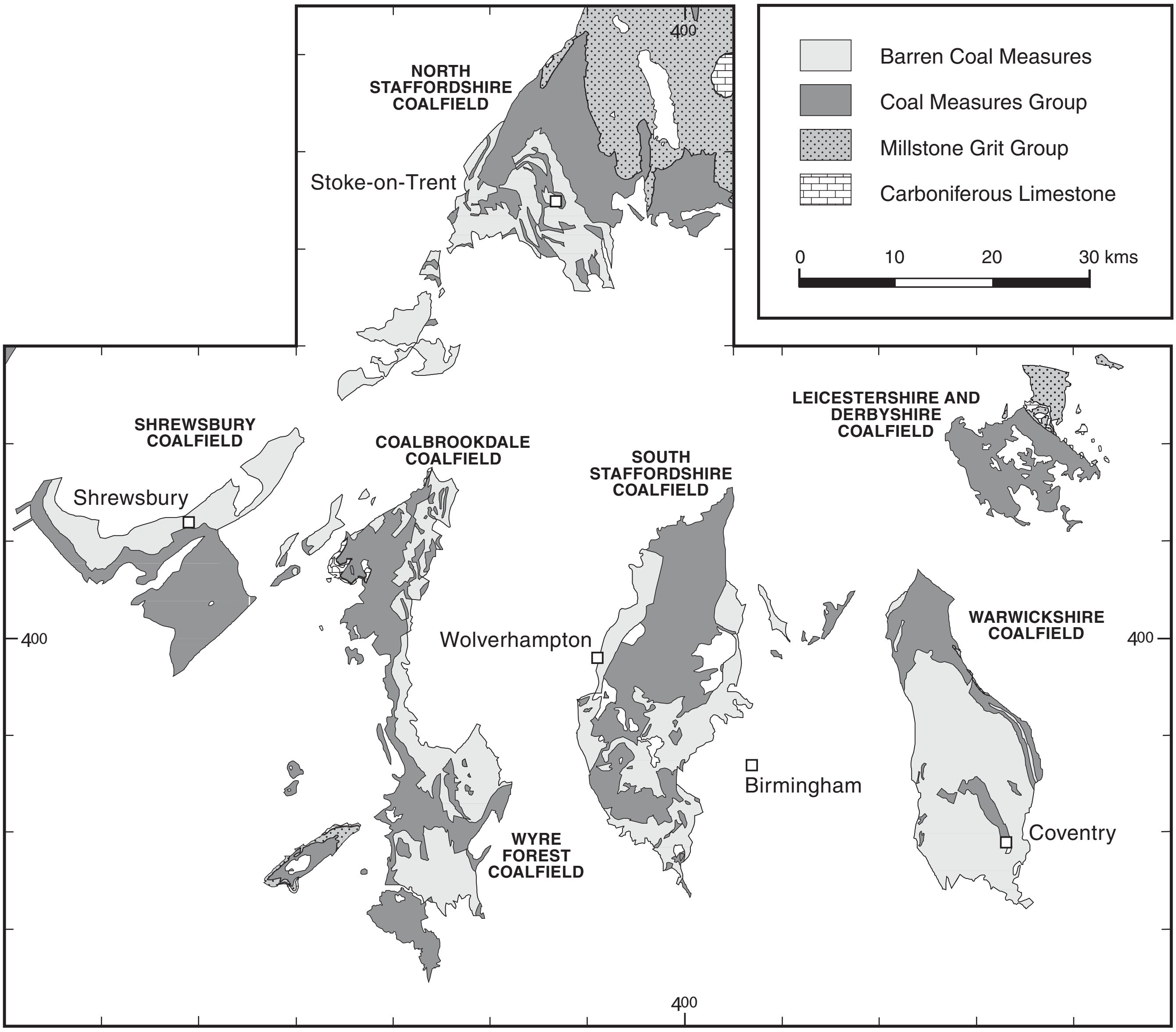


Figure 8.16 Distribution of Carboniferous outcrops in central England.

the section on the Pennines area (Section 8.6) and will therefore not be discussed further in this section.

The North Staffordshire Coalfield has a synclinal structure that plunges to the south-south-west and consists of a large roughly triangular area with two smaller areas to the east around Shaffalong and Cheadle. The coalfield covers an area of approximately 260 km^2. All four components from Lower Coal Measures to Barren Measures are represented in the main outcrop area.

The Leicestershire and South Derbyshire coalfields are separated by the south-south-easterly plunging Ashby Anticline. The outcrop area only amounts to about 60 km^2 with a considerably larger area concealed beneath younger Triassic strata. The Leicestershire Coalfield has a simple structure but the South Derbyshire Coalfield is extensively folded and faulted. The outcrop consists almost entirely of Lower and Middle Coal Measures with only a very small area of Upper Coal Measures.

The Warwickshire Coalfield extends southward from Tamworth to Warwick, is roughly oval in outline and covers an area of about 390 km^2. Much of the outcrop consists of Upper Coal and Barren Measures with the Lower and Middle Coal Measures occupying a narrow belt around the northern and north-eastern margin of the outcrop. The coalfield has a broad synclinal structure with steeply dipping margins and a gentle southerly plunge (Hains and Horton, 1969).

The South Staffordshire Coalfield is also roughly oval in shape extending southward from Rugeley to the Lickey Hills being bounded on the east and west by faults. The coalfield consists of a denuded north–south trending anticlinal structure. The full Coal Measures sequence (including the Barren Measures) is present.

The Coalbrookdale Coalfield extends southward from Lilleshall near Newport to Linley and is joined to the Wyre Forest Coalfield by a narrow outcrop. This coalfield commences near Bridgnorth to broaden and extend southward along the Severn valley. The Lower and Middle Coal Measures in this area were subject to deformation and erosion prior to the deposition of the Coalport Formation (Barren Measures). In consequence the thickness of the Lower and Middle Coal Measures is very variable, with the full thickness only being preserved in synclinal areas. The Upper Coal Measures are generally absent only having been preserved in the synclinal areas.

The Shrewsbury Coalfield outcrops in a broad gently curving area extending from the Breidden Hills near Alber-

Table 8.5 Stratigraphic framework for the Silesian rocks of the central England and Pennines area.

Epoch	**Chronostratigraphy**		**Lithostratigraphy (major units only)**	
Ma = million years before present	Series	Stage	Group	Formation
290 Ma	Stephanian		Barren Measures (Warwickshire) Group	See Table 8.6
	Westphalian	Westphalian D		
Silesian		Bolsovian (Westphalian C)	Coal Measures Group	Upper Coal Measures
(Upper Carboniferous)		Duckmantian (Westphalian B)		Middle Coal Measures
		Langsettian (Westphalian A)		Lower Coal Measures
327 Ma	Namurian	Yeadonian Marsdenian Kinderscoutian Alportian Chokierian Arnsbergian Pendleian	Millstone Grit Group (in south) or Stainmore Group (in north)*	

* Formerly Millstone Grit and Upper Limestone Group, together.

bury in the north to Haughmond Hill to the east of Shrewsbury. A further roughly rectangular area, (sometimes referred to as the Leebotwood Coalfield), lies to the south, its southern boundary being formed by the Church Stretton Fault. The Westphalian in this area consists entirely of Barren Measures but three workable coal seams are present within the Coed-yr-Allt Beds (the equivalent of the Newcastle or Halesowen Formations).

Dinantian

The Ticknall Limestone Formation outcrops as small inliers to the north of the Leicestershire Coalfield between Ticknall and Bredon on the Hill. Information from a single stratigraphic borehole suggests these limestones are underlain by over 80 m of Calke Abbey Sandstone Formation.

Namurian

The only Millstone Grit outcrop in the area apart from in north Staffordshire, is located on the northern flank of the Leicestershire Coalfield (Figure 8.16). The lower parts of the Namurian sequence, (the Pendleian and Arnsbergian) are absent, whilst the rest of the sequence is severely condensed. The Millstone Grit consists of a number of grit or sandstone horizons, separated by thick mudstones and shales. The four main grit horizons present in the area are the Rough Rock (at the top of the sequence), underlain by the Chatsworth Grit, the Ashover Grit (or lateral equivalents) and the Bottom Grit.

Westphalian

The Coal Measures have historically been subdivided into Lower, Middle and Upper Coal Measures, with the bases of the units defined as the bases of the Subcrenatum, Vanderbeckei and Cambriense marine bands, respectively. This nomenclature has persisted, with the exception of a redefinition of the Upper Coal Measures. Currently, the red strata have been assigned to a separate group, the Barren Measures or Warwickshire Group and the 'Upper Coal Measures' is used for strata of typical Coal Measures facies.

The Upper Coal Measures and Barren Measures (Warwickshire) Group successions for central England, including nomenclature equivalents formerly used across the area, are detailed in Table 8.6. Considerable revision of Upper Carboniferous nomenclature has occurred in recent years, often leading to some confusion. Figure 8.17 provides a summary of current Upper Carboniferous lithostratigraphic nomenclature for the West Midlands together with former classifications.

COAL MEASURES GROUP

The Coal Measures Group comprises alternations of pale grey sandstone, typically fine-grained and often ochreous weathered, grey siltstones and grey mudstones, with frequent coal seams, residual soil horizons and ironstones. There is a broad transition between the greater abundance of marine bands in the lower strata and of coal seams in the upper strata. Marine bands are less abundant than in the underlying Millstone Grit. The sandstones are generally lenticular, passing laterally as well as vertically into siltstones and mudstones. Sandstones associated with major channels may be up to 20 km wide, tens of kilometres long and greater than 8 m thick, often cross-bedded and with erosive bases which may be marked by conglomerates. Sandstones associated with minor channels are up to 1 km wide, several km long and up to 8 m thick and have variable components of sandstone, siltstone and mudstone. In the Lower Coal Measures sandstones are better developed to the north but thin and die out to the south and are absent in the Warwickshire Coalfield (Downing et al., 1970).

WARWICKSHIRE GROUP

The Barren Measures (Warwickshire) Group is composed of sandstones, siltstones and mudstones which are pre-

Table 8.6 Stratigraphic framework for the Upper Carboniferous (Silesian) rocks of central England (adapted from Powell, 1998).

	CENTRAL ENGLAND (excluding Warwickshire)		**WARWICKSHIRE**		
GROUP	**FORMATION**	**KEY MEMBERS**	**FORMATION**	**KEY MEMBERS**	**TYPICAL LITHOLOGIES**
Barren Measures (Warwickshire) Group (Upper Coal Measures)			**Ashow Formation** (Ashow Group; Whitmoor Marls and Whitmore Sandstone together)		red mudstone and sandstone
			Kenilworth Sandstone Formation (Kenilworth Breccia Group; Gibbet Hill Group)		red sandstone, thin mudstone and conglomerate
			Tile Hill Formation (Tile Hill Marl Group)		red mudstone and sandstone
			Meriden Formation (Keele Formation and Coventry Sandstone Formation together)	**Allesley Member** (Upper part of Coventry Sandstone Formation)	red mudstone, sandstone and conglomerate
	Salop Formation	**Enville Member** (Bowhills Formation; Calcareous Conglomerate Group)		**Keresley Member** (Middle part of Coventry Sandstone Formation)	
		Alveley Member (Keele Beds; Keele Formation)		**Whitacre Member** (Keele Formation and lower part of Coventry Sandstone Formation)	
	Halesowen Formation (Newcastle Formation; Highley Formation; Coalport Formation; Coed-yr-Allt Formation)				grey-green sandstone and mudstone with sparse, thin coal and limestone; locally reddened
	Etruria Formation (Etruria Marl; Old Hill Marl; Kinlet Formation; Hadley Formation; Ruabon Marl)				red or vari-coloured mudstone with beds of sandstone and conglomerate; sparse thin coals
Coal Measures Group (Productive Coal Measures)	Upper Coal Measures				grey mudstone and sandstone with seams of coal, ironstone and fireclay
	Middle Coal Measures				
	Lower Coal Measures				

dominantly reddish, brownish or purple grey in colour. Some grey strata, which are otherwise more commonly associated with the Coal Measures Group, are also present.

The Etruria Formation comprises red, purple, brown, ochreous and grey, commonly mottled mudstone with a dominant kaolinite clay mineralogy, with common pedogenic horizons but few coal seams, and subordinate lenticular green, coarse-grained to conglomeratic sandstones, known as 'espleys', rich in lithic detritus.

The Halesowen Formation comprises thick sandstone beds of grey-green micaceous lithic sandstone, locally pebbly, and grey-green mudstone with thin coals (less than 0.5 m thick) and thin limestone beds (Spirorbis Limestone). The strata locally show secondary reddening. The formation rests unconformably upon the Etruria Formation in south Staffordshire and Warwickshire.

The Salop Formation comprises two distinct members. A lower Alveley Member (equivalent to the Keele Formation) comprises a red mudstone-dominated succession with red, fine- to medium-grained sandstone and subordinate thin Spirorbis Limestone beds and pedogenic caliche. The overlying Enville Member typically is sandstone-dominated with red-brown, fine- to coarse-grained, locally pebbly sandstone and lenticular beds of conglomerate with common Carboniferous Limestone clasts, interbedded with red mudstones (Table 8.6).

The Meriden Formation consists of interbedded red mudstones, sandstones and subordinate thin conglomerates with a few thin beds of Spirorbis Limestone. The formation is subdivided into three members recognised as three upwards-coarsening cycles. The Coventry Sandstone, including the Corley Conglomerate, is a component of the Meriden Formation (Table 8.6).

8.5.1.2 *Structural geology*

Westphalian strata would originally have formed a thick continuous horizon extending over virtually all of central England. Subsequent folding, faulting and erosion preceded burial beneath younger Triassic strata. Erosion then removed considerable sections of Triassic cover exposing eight detached coalfields; namely the North Staffordshire, Leicestershire and South Derbyshire, Warwickshire, South Staffordshire, Shrewsbury, Wyre Forest and Coalbrookdale coalfields, as well as a small outlier on the Clee Hills (Figure 8.16).

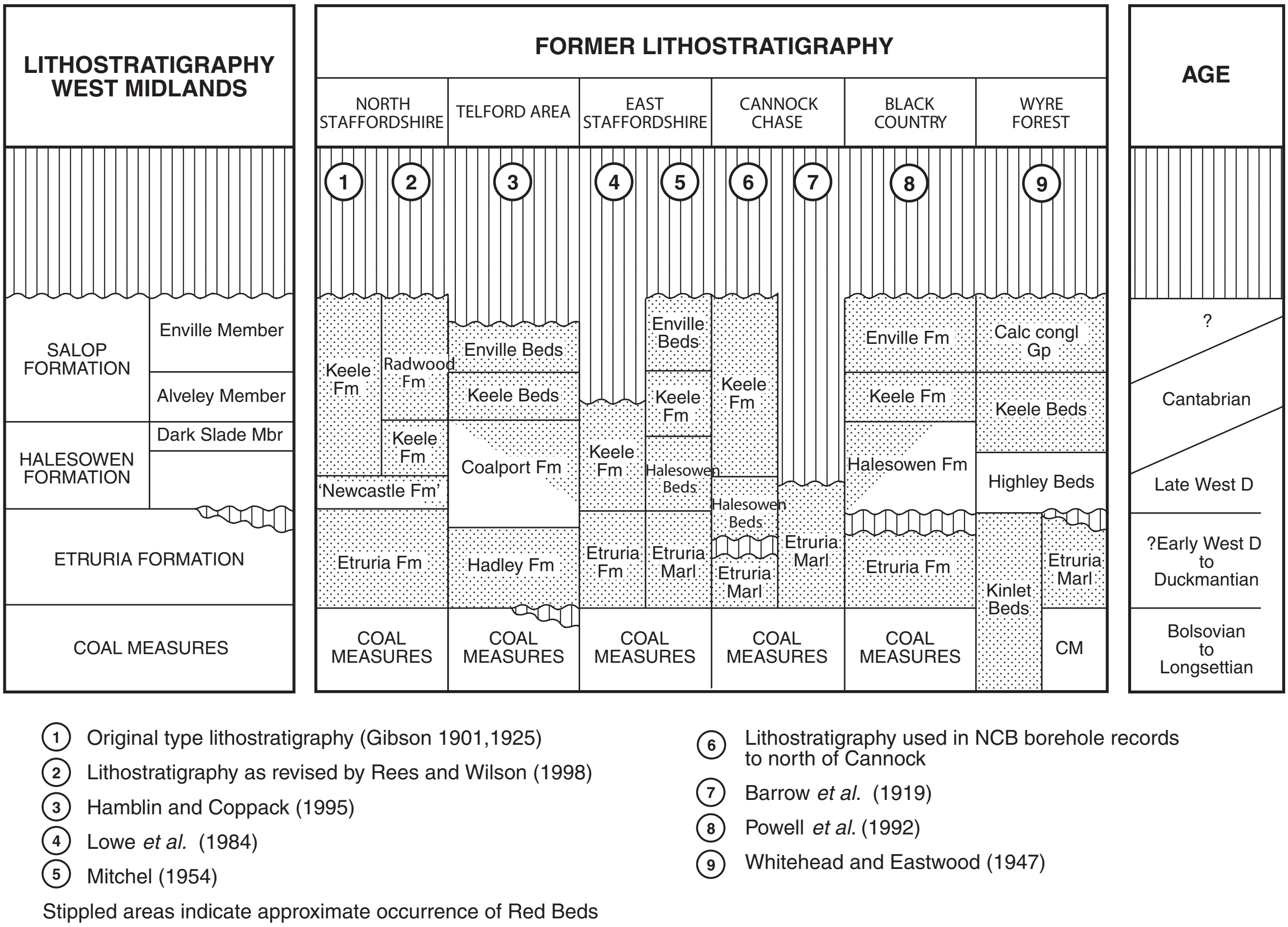


Figure 8.17 Summary of Upper Carboniferous lithostratigraphic nomenclature, showing former usage in various areas of the West Midlands (after Besly and Cleal, 1997).

8.5.2 Hydrogeology

8.5.2.1 *Introduction*

Dinantian

The presence of the Calke Abbey Sandstone Formation has only been shown in a single stratigraphic borehole and although geophysical logging can be interpreted to indicate the presence of fairly fresh water nothing further is known regarding its hydrogeological properties.

In the case of the Ticknall Limestone Formation, the outcrop area is too limited to provide any significant quantity of groundwater. Two boreholes at Weston-on-Trent obtained a supply from the limestones beneath Triassic Sandstones. The overlying sandstone is believed to have been cased out in one of these boreholes, which provided a yield of 545 m^3/d for a drawdown of almost 22 m (specific capacity of approximately 25 m^3/d/m). Boreholes which intersect water-bearing fractures of sufficient size are likely to provide usable yields. Failure to intersect water-bearing fractures in the limestones is likely to result in very low yielding or dry boreholes.

Namurian

These strata act as a multilayered aquifer system with the impermeable mudstones and shales acting as aquicludes between sandstone horizons which act as separate aquifer units. The sandstones are however generally well cemented and possess little primary porosity or permeability. Groundwater storage and movement is mainly dependent on the presence of fractures in the sandstones.

As is the case elsewhere, each grit or sandstone horizon acts as an individual aquifer separated by intervening impermeable mudstones and shales. Hydraulic continuity between aquifer horizons only occurs where faulting juxtaposes grit beds. The sandstones and grits are generally well cemented except where weathered near surface. Groundwater storage and movement is both intergranular and through fractures and joints in the grits but the latter will predominate at depth where the rocks are unweathered.

The availability of groundwater in the various grit horizons is quite variable; at Melbourne [SK 3801 2557] the Rough Rock and Chatsworth Grit were virtually dry but a supply was obtained from the deeper Ashover Grit. At Stanton [SK 3745 2715] however the Ashover Grit was virtually dry with artesian water being obtained from a fracture in the deeper Bottom Grit (Lewis, 1998). Yields from both springs and boreholes may vary seasonally and in some cases dry up in summer. Many of the aquifer horizons have only a small outcrop area and recharge is limited. Yields may therefore decline with time due to over-abstraction and consequent depletion of storage.

Westphalian

COAL MEASURES GROUP

Impermeable argillaceous rocks predominate in the Coal Measures Group (Lower, Middle and Upper) whilst sandstone horizons which could act as aquifers are generally thin, well-cemented and laterally impersistent. Both the argillaceous strata and well-cemented sandstones possess minimal primary porosity. Groundwater flow occurs in joints and fractures in the sandstones, often having been enhanced by mining subsidence. Borehole yields are dependent on the number and size of water bearing joints or fractures penetrated.

The Coal Measures Group constitutes a very minor source of groundwater across much of the central area. In the past, however, heavy pumping was necessary to drain mine workings, and this caused extensive dewatering in many areas. Of the coalfields in the area, the pits in the Derbyshire Coalfield were the wettest (Downing et al., 1970). With the closure of many mines and cessation of pumping, many abandoned workings have filled with groundwater. Very high yields are obtained from boreholes penetrating close to old flooded mine workings (Rees and Wilson, 1998) but the quality of such water is often poor. In the West Bromwich area, yields of 5520 to 6480 m^3/d have been obtained from 508 to 610 mm boreholes penetrating flooded abandoned workings (Downing et al., 1970), while the high-yielding Bradley Shaft provides canal make-up water. Few boreholes have been drilled into the Lower and Middle Coal Measures and yields have generally been 25 to 50 m^3/d or less. In the southern worked out section of the South Staffordshire Coalfield, boreholes of 305 to 380 mm diameter (which did not penetrate old workings) yielded 1080 to 2160 m^3/d, possibly due to greater amounts of structural deformation in the vicinity of the Sedgely-Dudley Anticline (Downing et al., 1970). Yields and borehole specific capacities also improve in the vicinity of the Eastern Boundary Fault (Powell et al., in press).

Local more persistent sandstone horizons can occasionally provide moderate quantities of water, for example in the northern Warwickshire Coalfield a sandstone located in the upper part of the Middle Coal Measures to the north of Coventry, referred to locally as the ‘4 Feet Sandstone’ (Richardson, 1928). In the Leicester and Derbyshire coalfields the Wingfield Flags, a micaceous fine grained flaggy sandstone, has sufficient lateral persistence to form a local aquifer. A yield of almost 550 m^3/d was obtained from a 200 mm diameter borehole which penetrated 24.4 m of the sandstones at Ashby-de-la-Zouch [SK 3516 1785] (Lewis, 1998) whilst over 1080 m^3/d was obtained from the Wingfield Flags at Heather Pumping Station [SK 394 107]. Recharge to these strata is severely restricted due to the presence of impermeable cover, and uncertainty whether yields can be sustained over time limits the extent to which this horizon can be developed for abstraction.

Barren Measures (Warwickshire) Group

The Etruria Marl (or Ruabon Marl in the west) at the base of the Barren Measures, is composed predominantly of impermeable argillaceous rocks and yields little or no water. Fractures in the ‘espley’ rocks, however, can yield moderate quantities of water suitable for small-scale agricultural or industrial requirements (Downing et al., 1970; Barrow et al., 1919). Although the ‘espley’ rocks are generally well cemented, in south Staffordshire they often have a more sandy and porous matrix and may yield a good supply.

Sandstones contained in the remainder of the Barren Measures strata are capable of yielding moderate, and occasionally large, quantities of groundwater.

The Tile Hill Mudstone, at the top of the Barren Measures, is not generally considered an aquifer, being predominantly composed of impermeable argillaceous rocks.

8.5.2.2 *Core data*

Dinantian

The Calke Abbey Sandstone Formation has porosities in the range of 10.2 to 19.3% whilst porosities of up to 9.4% were measured for core samples from the Ticknall Limestone Formation (Entwisle, 1996). No permeability data are available for either formation.

Five core samples from unspecified Dinantian strata at depths of between 78 and 143 m in the Rotherwood Borehole [SK 3651 6400], gave porosity values in the range of 3 to 18% (average 7%).

Namurian

Porosities of between 24 and 36% (average about 28%) and permeability ranging from 0.14 to 1.7 m/d (238 to 2524 mD) have been measured for grit/sandstone samples obtained from outcrop in the Leicester/south Derbyshire area [SK 3835 2493] (Lewis, 1998). Since these samples would have been subject to weathering, values at depth in unweathered horizons are likely to be considerably lower. No data are however available for unweathered rock core samples in the area.

Westphalian

Coal Measures Group

There are no known values of porosity or permeability for Lower Coal Measures Group core or outcrop samples. Values are however available for younger Coal Measures for two outcrop samples from an outcrop at Saltwells Pit [SO 9353 8704] (average porosity and permeability values of 13.5% and 4.2 × 10^{-4} m/d) and a single sample from a depth of 74.7 m from a borehole at Snarestone Lodge [SK 3433 1015] (16.8% and 4.2 × 10^{-4} m/d).

Barren Measures Group

Porosity and permeability values are available for eight outcrop locations and for core samples from six boreholes penetrating the Barren Measures Group in the central area, (including two outcrop and one borehole sample in the North Staffordshire Coalfield). The samples were likely to have been predominantly biased towards sandstone lithologies but it is not possible to determine from which formation the samples originated. Porosity values for the outcrop samples ranged from 8 to 31% with an arithmetic mean of 23% and median value of 22.5%. Porosities for the core samples were somewhat lower, ranging from 3 to 28% with arithmetic mean and median values of 16 and 15% respectively. Outcrop permeability values ranged between 4.6 × 10^{-4} and 2.2 m/d (1 to 3280 mD) with arithmetic mean and median values of 0.6 m/d (938 mD) and 8 × 10^{-2} m/d (141 mD). Corresponding values for the borehole core samples were 3 × 10^{-6} to 1 m/d (1 × 10^{-2} to 1657 mD), 0.16 m/d (269 mD) and 3.3 × 10^{-3} m/d (7 mD). As may be expected the values of both porosity and permeability for weathered outcrop samples are higher than those originating from relatively unweathered borehole core samples. Whilst the data set available is relatively limited and not necessarily representative of the Barren Measures Group as a whole, it does seem to indicate resource potential for these strata.

Lerner et al. (1993) reported that hydraulic conductivity of sandstone samples from a coal exploration borehole in the Meriden Formation, lay in the range of 10^{-4} to 0.58 m/d with 80% of values in the range of 10^{-4} to 10^{-2} m/d. Porosities were in the range of 5 to 22% with a median of 11%. An estimate of fracture porosity of 0.3% was also provided.

Hydraulic conductivities obtained from packer testing ranged from 0.01 to 2.88 m/d; the greater magnitude of these values, as compared to intergranular measurements, indicates the importance of fracture flow in the sandstone units.

8.5.2.3 *Pumping test results*

Dinatian and Namurian

Aquifer test results for the Carboniferous Limestone in the central area are covered in Allen et al (1997). No test results are available for the Millstone Grit in this area.

Westphalian

All Westphalian test values contained in the Minor Aquifers Database are categorised as Coal Measures or Lower, Middle or Upper Coal Measures in keeping with the nomenclature in common usage until recently. Although Lower or Middle Coal Measures values are attributable to the Coal Measures Group, it is believed that few if any data classed as Upper Coal Measures should be assigned to the Coal Measures Group. These instead are classed as Barren Measures Group. This assumption can be confirmed where more detailed stratigraphic names are available (eg. The Coventry Sandstone, Enville Beds, Keele and Halesowen formations, Barren Coal Measures). In view of the very limited outcrop area of the Coal Measures Group in the South Staffordshire and Warwickshire coalfield area, (where most sites are located), it is probable that most unclassified Coal Measures sites may also be attributable to the Barren Measures Group.

Sites where pumping test values exist are heavily concentrated in the South Staffordshire and Warwickshire coalfields, with none located in the Leicestershire/South Derbyshire coalfields. There are two each in the Wyre Forest and Coalbrookdale, three in the North Staffordshire Coalfield and a single Upper Coal Measures site in the Shrewsbury Coalfield.

COAL MEASURES GROUP

Transmissivity and storage coefficient

The two transmissivity values available for the Middle Coal Measures are markedly different (2 and 377 m^2/d). For the reason stated above, these values are not likely to be representative of the Coal Measures Group as a whole. No storage coefficients are recorded.

Specific capacity

Specific capacities are available for five Coal Measures Group boreholes; one of the Lower Coal Measures and four of the Middle Coal Measures. A further nine sites are attributed to unspecified Coal Measures but the majority of these are in fact likely to have penetrated the Barren Measures.

The sole Lower Coal Measures specific capacity is 36.4 $m^3/d/m$, whilst Middle Coal Measures values range from 2 to almost 90 $m^3/d/m$ with an extreme value of over 650 $m^3/d/m$; this latter value was for the same site as the abnormally high transmissivity value cited above. Although 37 m deep, no diameter is recorded for the latter site but it is probable that it is a large diameter shaft.

BARREN MEASURES GROUP

Test results for the Barren Measures Group are heavily concentrated in the Warwickshire Coalfield area with only four in the South Staffordshire Coalfield, two in the Coalbrookdale and one in each of the North Staffordshire and Shrewsbury coalfields. A summary of aquifer properties data for the Barren Measures Group as a whole and for particular horizons within the group is shown in Table 8.7.

Figures 8.18 and 8.19 show the distribution histogram and cumulative frequency plots of transmissivity and specific capacity for the Barren Measures Group as a whole. Figure 8.20 shows that there is not a linear relationship between specific capacity and transmissivity; most points group below values of specific capacity of 300 $m^3/d/m$ and transmissivity of 300 m^2/d.

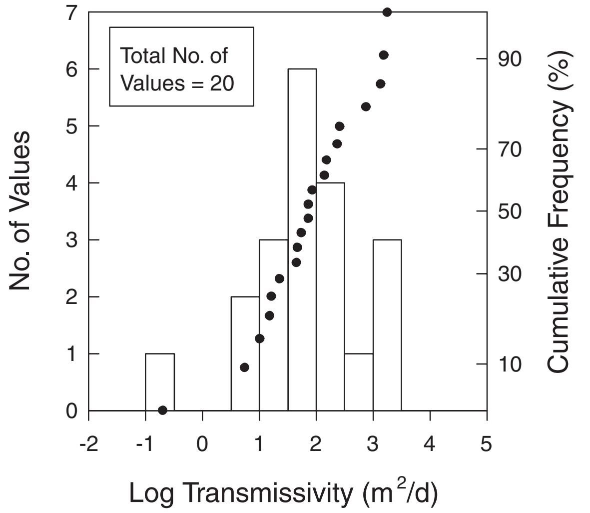


Figure 8.18 Distribution of transmissivity data from pumping tests in the Barren Measures Group of central England.

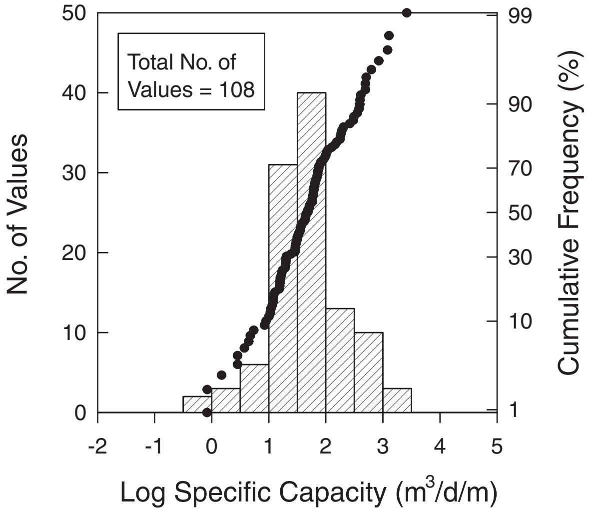


Figure 8.19 Distribution of specific capacity data from pumping tests in the Barren Measures Group of central England.

Transmissivity and storage coefficient

Transmissivity values vary widely for the Barren Measures Group as a whole, reflecting the highly variable presence of fractures and sandstone thicknesses. Compared to the number of specific capacities available, few aquifer tests were conducted and/or analysed to provide transmissivity values. The single transmissivity value for the Halesowen Formation is not likely to be representative. However, comparison of the datasets of the Halesowen, Salop and Meriden formations suggests the upper parts may be more productive than the group as a whole, and the lower parts of the Salop and Meriden formations somewhat less productive. A single storage coefficient is indicative of semi-confined to confined conditions.

Bishop et al. (1993) reported the results of two constant rate pumping tests carried out on sandstone units of the Meriden Formation. One provided a transmissivity of 26 m^2/d and corresponding hydraulic conductivity of 3.3 m/d for the sandstones whilst the second gave a transmissivity value of 17 m^2/d, a hydraulic conductivity of 1.7 m/d and storage coefficient of 4×10^{-3}.

Specific capacity

Three values of specific capacity were available for the Etruria Marl (10 to 37 m^3/d/m). However, considering the fact that boreholes with sufficient yields to justify testing are very rare, these cannot be considered representative.

The relatively few values from the Halesowen Formation are possibly due to rapidly declining yields with time. The large range of values presumably reflects the varying presence and size of fractures in the formation. In the west, two tests at a site in the Coalport Formation (the lateral equivalent of the Halesowen Formation) provided values of 144 and 74 m^3/d/m. The lower maximum and minimum values for the Keele Formation (now the Alveley Member of the Salop Formation or lower part of the Whitacre Member of the Meriden Formation) is a reflection of the poor water bearing properties of this horizon as compared to both the Halesowen Formation and Enville Bed/Coventry Sandstone (now the Enville Member of the Salop Formation or upper part of the Meriden Formation).

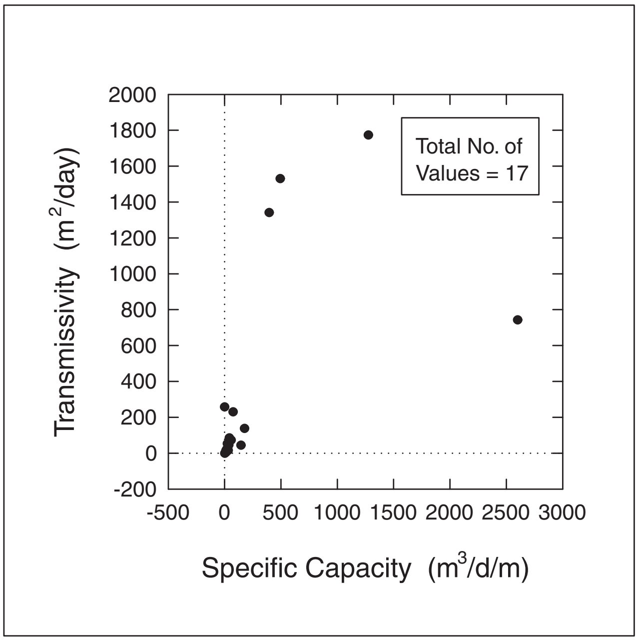


Figure 8.20 Correlation between specific capacity and transmissivity for the Barren Measures Group of central England.

8.5.2.4 *Yield data*

Namurian

Yields ranging from 336 to 696 m^3/d have been obtained from 150 to 250 mm diameter boreholes penetrating one or more grit horizons either in Millstone Grit outcrop areas or beneath the overlying Mercia Mudstone. The highest yields are obtained from groups of wells interconnected by adits, which maximise the potential for penetrating water bearing fractures (Lewis, 1998). Adits are no longer constructed, and such yields are not typical. Productivity can often be below this range with some boreholes being dry.

Westphalian

Downing et al. (1970) analysed the range of yields recorded for various sizes of wells penetrating the Barren Measures in the Trent river basin which overlies much of the total area of Carboniferous strata. The analysis appears to be representative of the central area as a whole. The original table has been adapted to provide yields in m^3/d using current stratigraphic nomenclature, namely the Halesowen Formation (or Newcastle Formation in north Staffordshire), Enville and Alveley members (Salop Formation) or Whitacre Member (Meriden Formation) (Table 8.8).

The yield ranges in Table 8.8 are, in many cases, for tests of short duration. Long term sustainable yields may be appreciably less at some sites. It should also be recognised that low yielding boreholes are unlikely to have been tested and so the data are biased towards higher yields. Many boreholes and shafts penetrate more than one horizon of the Barren Measures Group so it is not possible to determine the contribution to the total yield from any particular horizon.

The largest yields from the Barren Measures have been obtained from the thick, often massive sandstones of the Halesowen Formation, which have been widely exploited in the South Staffordshire and Warwickshire coalfields. Particularly high yields were obtained from a thick persistent sandstone, (known colloquially as the '100 Foot' sandstone by virtue of its average thickness), at the base of the Halesowen Formation in the northern part of the Warwickshire Coalfield (Richardson, 1928b). Initial yields from this horizon were invariably large and on occasions presented major problems for the construction of mine shafts. At Whittleford [SP 3281 9186] inflow rates (of over 1920 m^3/d) were so great as to prevent the completion of a pair of shafts. A gradual decline of yield with time is common to virtually all shafts, wells and boreholes penetrating this sandstone, the outcrop area and hence recharge being limited. At Baxterly Well [SP 2831 9607] and Exhall Colliery initial yields of 3192 and 9840 m^3/d declined to 288 and 1128 m^3/d respectively over a period of only two years; at Haunchwood Colliery, a yield of 1296 m^3/d declined to 312 m^3/d (Bridge et al., 1994). This led to the conclusion that yields from this sandstone could be expected to decrease by more than half per mile distance from outcrop (Richardson, 1928b).

Yields from the Halesowen Formation have also been affected by mining activities; for example at Hawkesbury Pumping Station a large diameter well, initially capable of yielding 6912 m^3/d, was derogated by heavy mine drainage pumping at nearby Exhall Colliery (Bridge et al., 1994). The role of fractures in the sandstones as a major factor in determining yield is demonstrated at Dexter Colliery where, during shaft sinking, a yield of 2184 m^3/d was obtained from a single 64 cm wide fracture (Downing et al., 1970).

Table 8.7 Summary of aquifer properties data for the Carboniferous Barren Measures Group in the central area.

Barren Measures Group		
Number of transmissivity records	20	—
Minimum/maximum transmissivity value (m^2/d)	0.2	1774
Arithmetic/geometric mean of transmissivity (m^2/d)	331	71
Median/inter-quartile range of transmissivity (m^2/d)	73	233
25/75 percentile range of transmissivity (m^2/d)	17	251
Number of storage coefficient records	1	—
Maximum/minimum storage coefficient	6.4×10^{-4}	6.4×10^{-4}
Number of specific capacity records	108	-
Minimum/maximum specific capacity (m^3/d/m)	0.8	2600
Arithmetic/geometric mean of specific capacity (m^3/d/m)	141	46
Median /inter-quartile range of specific capacity (m^3/d/m)	47	81
25/75 percentile of specific capacity (m^3/d/m)	18	99
Halesowen Formation		
Number of transmissivity records	1	—
Minimum/maximum transmissivity value (m^2/d)	1774	1774
Number of storage coefficient records	0	—
Number of specific capacity records	7	—
Minimum/maximum specific capacity (m^3/d/m)	12.03	1274
Salop Formation/Meriden Formation **Alveley Member/Lower Whitacre Member (Keele Formation)**		
Number of transmissivity records	4	—
Minimum/maximum transmissivity value (m^2/d)	16	1531
Arithmetic/geometric mean of transmissivity (m2/d)	405	74
Number of storage coefficient records	0	—
Number of specific capacity records	15	—
Minimum/maximum specific capacity (m^3/d/m)	0.8	506
Arithmetic/geometric mean of specific capacity (m^3/d/m)	169	72
Median /inter-quartile range of specific capacity (m^3/d/m)	—	—
25/75 percentile of specific capacity (m^3/d/m)	24	303
Salop Formation/Meriden Formation **Enville Member/Upper Whitacre Member (Enville Beds/Coventry Sandstone)**		
Number of transmissivity records	1	—
Minimum/maximum transmissivity value (m^2/d)	258	258
Number of storage coefficient records	1	—
Maximum/minimum storage coefficient	6.4×10^{-4}	6.4×10^{-4}
Number of specific capacity records	75	—
Minimum/maximum specific capacity (m^3/d/m)	0.8	1204
Arithmetic/geometric mean of specific capacity (m^3/d/m)	98	39
Median /inter-quartile range of specific capacity (m^3/d/m)	41	55
25/75 percentile of specific capacity (m^3/d/m)	17	72

In the South Staffordshire Coalfield yields from the Halesowen Formation generally range from 432 to 1920 m^3/d. In the North Staffordshire Coalfield, yields are markedly smaller from the stratigraphically equivalent Newcastle Group, since the thick massive sandstones of the former are absent. One or two boreholes, which penetrate both the Keele and Newcastle Formation, have however exceptionally yielded as much as 1296 m^3/d (Downing et al., 1970). Little information is available regarding yields from the Coalport Formation, (the stratigraphic equivalent in the west of the area), but they would appear to range from about 25 to 168 m^3/d, again due to a lack of thick sandstone horizons.

The higher yields from the Meriden (Warwickshire Coalfield) and Salop (South Staffordshire Coalfield) formations are generally obtained from boreholes and wells which penetrate more than one sandstone unit. Since many sources penetrate several sandstone horizons it is generally difficult to ascribe yields or other hydrogeological characteristics to any particular part of the sequence. Severn Trent Water (1986) considered that the yield generally reflected the amount of sandstone penetrated in a borehole.

The Alveley Member or lower part of the Whitacre Member, (approximately the equivalent of the former Keele Formation), tends to provide only limited yields, with the range shown in Table 8.8 being typical of the south Staffordshire and Warwickshire areas but generally less in north Staffordshire. In the Coventry area, a more laterally extensive sandstone, known colloquially as the '40 Foot' sandstone, has traditionally been recognised as providing

Table 8.8 Yield ranges obtainable from the Barren Measures Group.

Formation	**Member**	**Yield (m^3/d)**			
		Borehole diameter (mm)			
		Up to 203	*203 to 406*	*406 to 610*	*Shafts with or without adits*
Salop or lower Meriden Formation (S Staffs/Warwics)	Enville Member/ upper part Whitacre Member	33.6 to 64.8	108 to 874	no data	2160 to 4320
	Alveley Member/ lower part Whitacre Member (Keele Formation)	Up to 108	Up to 545	Little increase in yield over 406 mm diameter	
Halesowen Formation (S Staffs+ Warwickshire)		Up to 218	218 to 1092	1092 to 2160	From 2160 to as much as 9816
Newcastle Formation (N Staffs)		Maximum discharge probably not more than 437			

better yields. This sandstone, positioned near the base of the Whitacre Member is very well cemented and groundwater movement is almost entirely via fractures. Like the ‘100 Foot’ sandstone of the Halesowen Formation the ‘40 Foot’ also has limited outcrop and recharge. Initially large yields have in some cases declined with time, although not as dramatically as for the ‘100 Foot’. Yields from sandstones at the base of the Whitacre Member in the Coventry area generally range from 696 to 1296 m^3/d for very variable amounts of drawdown but exceptionally yielded 3288 m^3/d from a 250 mm diameter borehole at Foleshill [SP 3519 8271].

The best yields from the Enville Member and upper part of the Whitacre Member (the approximate equivalent of the former Enville Beds) appear to have been obtained from large diameter shafts. In the Coventry area large diameter boreholes and wells penetrating the Enville Member have provided important public supply sources, some of which remain in current use. Yields in excess of 4000 m^3/d have been reported (Elfyn Parry, personal communication). No information is available regarding yields from the lateral equivalents of the Salop Formation in the west of the area where argillaceous strata predominate and outcrop area is small.

The Corley Sandstone in the Keresley Member of the Meriden Formation constitutes the most important water-bearing horizon in the western part of the Warwickshire Coalfield with yields ranging from 34 to 53 m^3/d (Powell et al., in press). In the Meriden Formation as a whole shallow wells and boreholes which did not penetrate any of the major sandstone horizons generally yield between 25 and 50 m^3/d; dry boreholes are rare.

An examination of Barren Measures Group yields held on the Aquifer Properties Database shows that the highest values are concentrated in the Warwickshire Coalfield area.

8.6 THE PENNINES

8.6.1 Geology and stratigraphy

The Askrigg Massif in the north of the Pennines area consists predominantly of Carboniferous limestones which extend to the west around Morecambe Bay and along the southern fringe of the Lake District to Barrow-in-Furness. The main Pennines Carboniferous Limestone outcrop extends southward to the Malham area, swinging south-westwards towards Clitheroe before disappearing beneath overlying Triassic sandstones to the north of Preston (Figure 8.21).

In the north of the area outliers of Millstone Grit form conspicuous hills above lower-lying Carboniferous Limestone terrain. In the east the Millstone Grit outcrop extends in a broad belt from Barnard Castle to the Leeds and Bradford areas, then narrowing along the central Pennines to the south where the outcrop almost encircles the Carboniferous Limestone outcrop of the Peak District in Derbyshire. A narrower outcrop extends south-westwards from the Keighley area to Blackburn in Lancashire, where two further main outcrop areas constitute the Lancaster Fells and Rossendale Hills. A further roughly rectangular area extends inland from Lancaster in the west (Figure 8.21).

There are two main areas of Coal Measures Group in the area, located to the east and west of the Pennines. The Lancashire Coalfield outcrop has a roughly triangular outcrop extending from the Skelmersdale/St Helens area in the west, to Burnley in the north and Macclesfield in the south-east. A number of small outliers outcrop to the south. The roughly triangular outcrop of the North Staffordshire Coalfield centred on Newcastle-under-Lyme has been previously discussed as part of the Central area (8.5.1). To the east of the Pennines the Yorkshire/East Midlands Coalfield extends between Leeds and Bradford in the north, tapering southward to Nottingham (Figure 8.21).

8.6.1.1 *Extent of aquifer group, stratigraphy and lithology*

Dinantian

The Craven Basin (Figure 8.2) is marked by the predominance of basinal dark bituminous limestones and mudstones and relatively limited development of reef limestones, (the Chatburn Limestone). The uppermost Dinantian strata, the Bowland Shale Group, comprise dark organic-rich mudstones with varying proportions of fine-grained

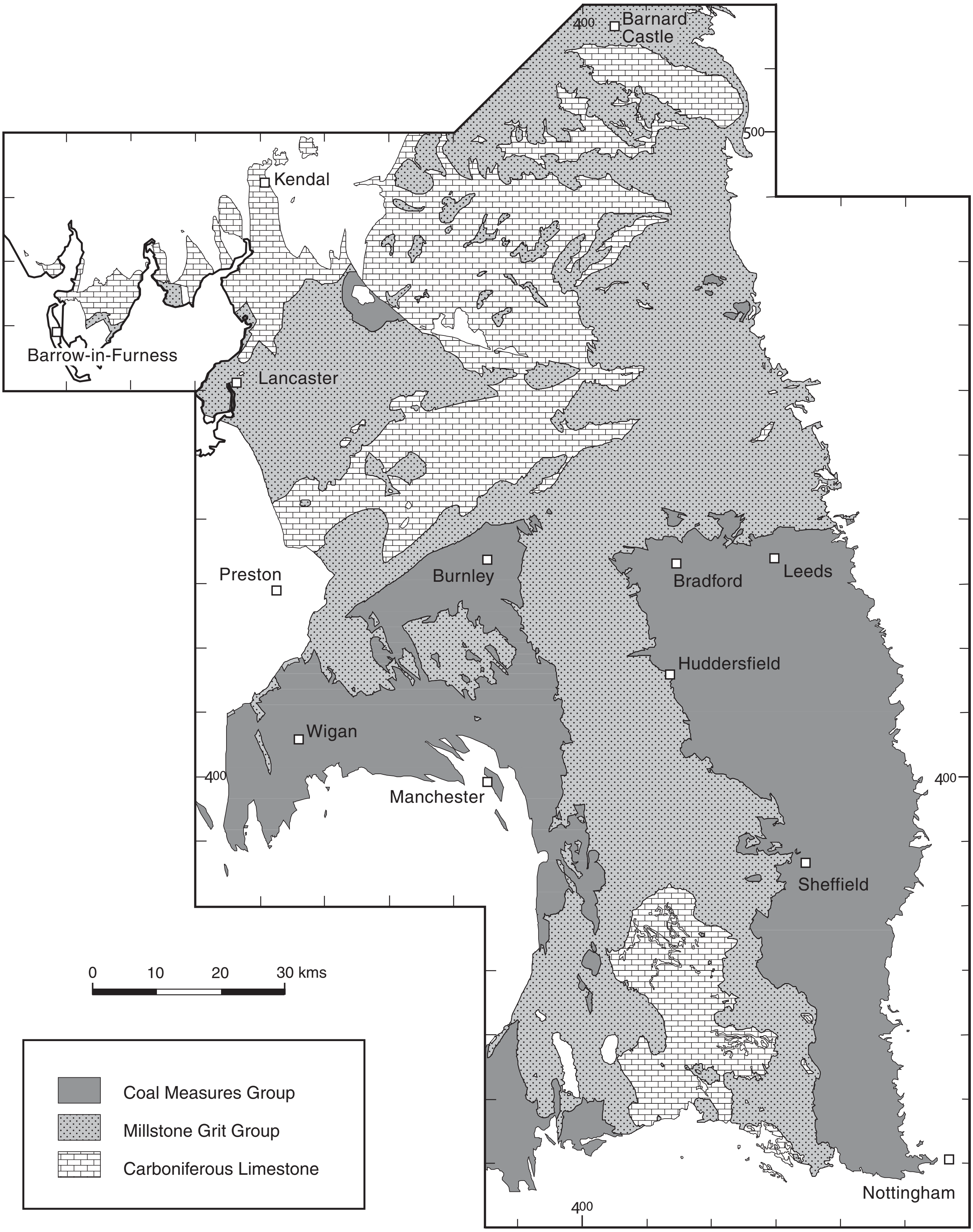


Figure 8.21 Distribution of Carboniferous outcrops in the Pennines.

turbiditic limestones, sandstones and siltstones, which continued to be deposited into Namurian times.

In the Askrigg Block (Figure 8.2) area the lower Dinantian strata comprise thick-bedded grey limestones, typically bioclastic and often ooidal, of the Great Scar Limestone Group with thin beds of mudstone and siltstone. Along the southern margin of the Askrigg Block the carbonates were deposited in the form of apron reefs and discrete knoll reefs. In the northern Pennines, the uppermost Dinantian strata are the Wensleydale Group of the Askrigg Block, and the upper part of the Alston Group of the Stainmore Trough and Alston Block. These comprise the typical 'Yoredale facies' of cyclical beds with a typical upward succession of limestone, mudstone, siltstone, sandstone, residual soil, and coal. The limestones are typically most prominent in the south of the Askrigg Block, where they are grey, thick-bedded and bioclastic.

Namurian

The Millstone Grit typically comprises coarsening-upward cycles ranging from dark grey carbonaceous shales, grey silty mudstones and siltstones, fine- to very coarse-grained feldspathic sandstones (formerly referred to as grits) with subordinate coals and residual soil horizons typically capping the cycles in the upper part of the group. The proportion of sandstone to mudstone broadly increases upwards within the group as a whole. The sandstones are often upward coarsening with gradational bases and sharp tops, representing progradation of delta top sand-bodies. However, many of the thick delta-top sandstones occupy major distributary channels and may be upward fining and have sharp erosive bases. Sandstones can range from coarse-grained and cross-bedded or massive to fine-grained, micaceous and thinly planar laminated. The Rough Rock is typically a coarse-grained, pebbly, cross-bedded sandstone marked by a sharp erosive base. However, locally in the central Pennines the Rough Rock is underlain by a typically fine- to medium-grained, micaceous, flaggy sandstone, the Rough Rock Flags, which have a gradational base comprising upward-coarsening and upward-thickening beds of sandstone interbedded with siltstone and silty mudstone. The Chatsworth Grit of Derbyshire is lithologically similar to the Rough Rock, though it passes northwards into the Huddersfield White Rock of the central and southern Pennines which is typically fine-grained.

The Pendle Grit Formation is distinguished by the presence of laterally impersistent, medium- to coarse-grained feldspathic sandstones, typically sharp-based and massive, interbedded with subordinate siltstone and mudstone. These strata are interpreted as being deposited as delta-slope turbidites. The Pendle Grit Formation is restricted to the Pendleian in age. However, this turbidite facies moved southwards as a consequence of the progradation of deltaic sediments into the Pennine Basin such that in north Staffordshire they are Marsdenian in age.

The Pendle Grit Formation is limited in extent to the northern margin of the Pennine Basin, notably in the Craven Basin of Lancashire and Yorkshire, where it forms the oldest strata of the Millstone Grit. The Kinderscout Grit, or equivalent sandstones, are more extensive, occurring across the central and south Pennines. Marsdenian sandstones are laterally extensive, though tend to be given local names. For example, the Ashover Grit and Roaches Grit are named relative to their position on the eastern and western margin of the Derbyshire Dome, respectively. The Revidge Grit is a name applied only in Lancashire where it may also be known as the Gorpley Grit; the equivalent in Yorkshire is named the Midgley, Pule Hill or Brandon Grit. The Rough Rock is the most laterally extensive sandstone in the Millstone Grit Group occurring over most of the Pennine Basin (Table 8.9).

Westphalian

The Coal Measures have historically been subdivided into Lower, Middle and Upper Coal Measures. The bases of the units defined as the bases of the Subcrenatum, Vanderbeckei and Cambriense Marine Bands, respectively. This nomenclature has been continued, with the exception of a redefinition of the Upper Coal Measures. The Upper Coal Measures in the Pennines area comprise all Carboniferous strata present above the Cambriense Marine Band apart from limited areas of south Lancashire, where red beds are present, which are considered to constitute part of the Barren Measures Group. Westphalian stratigraphic subdivisions are based upon laterally extensive marine bands and coal seams which in general have little hydrogeological significance. The main stratigraphic sub-divisions together with schematic lithological logs for the Westphalian strata to the east and west of the Pennines are shown in Figures 8.22 and 8.23 respectively. The two figures indicate the stratigraphic positions of the more important sandstones and their lateral relationships.

The Coal Measures Group comprises alternations of pale grey sandstone, typically fine-grained and often ochreous weathered, grey siltstones and grey mudstones, with frequent coal seams, residual soil horizons and ironstones. There is a broad transition between the greater abundance of marine bands in the lower strata, and of coal seams in the upper strata. The marine bands are less abundant than in the underlying Millstone Grit. The sandstones are generally lenticular, passing laterally as well as vertically into siltstones and mudstones. Sandstones associated with major channels may be up to 20 km wide, tens of kilometres long and greater than 8 m thick, often cross-bedded and with erosive bases which may be marked by conglomerates. Sandstones associated with minor channels are up to 1 km wide, several kilometres long and up to 8 m thick and have variable components of sandstone, siltstone and mudstone.

Although argillaceous rocks predominate throughout the Coal Measures, sandstones are generally more common and attain greater thicknesses to the west of the Pennines. To the east of the Pennines the sandstones are thickest in the Yorkshire Coalfield, thinning and becoming less common to the south in the East Midlands Coalfield.

8.6.2 Hydrogeology

8.6.2.1 *Introduction*

Parts of the area considered in this section are covered by the Hydrogeological Maps of Southern Yorkshire (Institute of Geological Sciences, 1982b), the Northern East Midlands (Institute of Geological Sciences, 1981) and Clwyd and the Cheshire Basin (British Geological Survey, 1989). These provide information on the hydrogeological properties and groundwater chemistry of the various strata underlying the area. Downing et al. (1970) and Gray et al. (1969) carried out detailed studies of the hydrogeology of the catchments of the Rivers Trent and Ouse which are both partially underlain by Carboniferous strata. Ineson (1953) reported on the hydrogeology of parts of Derbyshire and Nottinghamshire with particular reference to the Coal Measures.

Table 8.9 Namurian strata of the Bradford and Sheffield areas (after Powell, 1998).

Group	Sandstones and grits in the Bradford area	Typical lithologies in the Bradford area (*sst = sandstone)	Sandstones and grits in the Sheffield area	
Millstone Grit Group** (Namurian strata) (**mudstone and siltstone with named sandstones)	Rough Rock	pebbly, coarse-grained sst	Rough Rock	
	Rough Rock Flags	fine- to medium-grained sst		
	Huddersfield White Rock	pale grey, fine-grained sst	Redmires Flags Chatsworth Grit	
	Guiseley Grit	fine- to coarse-grained sst	Ashover Grit	Roaches Grit
				Curbar Grit
	Midgley Grit	coarse-grained sst	Heyden Rock	
	Scotland Flags	fine- to medium-grained sst	undivided Millstone Grit	
	Keighley Bluestone	blue-grey, siliceous siltstone		
	East Carlton Grit	fine- to coarse-grained sst		
	High Moor Sandstone	fine- to coarse-grained sst	Upper Kinderscout Grit	
	Doubler Stones	fine- to coarse-grained sst	Lower Kinderscout Grit	
	Long Ridge Sandstone	fine- to coarse-grained sst		
	Addingham Edge Grit	pebbly sst		
	Brocka Bank Grit	medium- to coarse-grained sst	Shale Grit	
	Middleton Grit	fine- to coarse-grained sst	Mam Tor Beds	
	Nesfield Sandstone	fine-grained, quartzose sst	undivided Millstone Grit	
	Marchup Grit	Medium- to coarse-grained sst		
	Bradley Flags	fine-grained, thin bedded sst		
	Warley Wise Grit Fm	coarse-grained, pebbly sst		
	Pendle Grit Formation	coarse-grained sst		

Dinantian

The hydrogeology and aquifer properties of the Carboniferous Limestone in the Peak District have previously been described in detail in Allen et al. (1997) and will not therefore be considered further here.

The nature of the Carboniferous Limestone aquifer varies considerably across the rest of the Pennines area. The limestones are water-bearing where dissolution has produced flow systems, whilst the interbedded shales and mudstones act as aquicludes or aquitards. The amount of limestone present varies greatly; massive limestones with relatively minor interbedded mudstones occur in northern Yorkshire but shales predominate in the Craven district and the north-west of the area. The distribution of the various dominant Carboniferous Limestone lithologies is shown in Figure 8.24.

The matrix of the limestones has a very low porosity and permeability, making a negligible contribution to total groundwater flow. The limestones only constitute an aquifer due to the presence of a secondary network of solution enlarged fractures and joints, which often form complex branching systems, ranging in scale from extensive cave systems to microfractures. Groundwater flow in such well developed karstic terrain is largely concentrated in the larger conduits and directed towards discrete points of discharge (single springs or groups of springs). Groundwater flow directions are often difficult to predict and may change markedly with variations in water table levels as discrete channel networks are dewatered.

Doughty (1968) identified three types of joints in the Great Scar Limestone in the Craven area; conjugate, tension and low angle joints. Of these, the conjugate joints have the greatest lateral extent and are almost invariably orientated within 10Þ of vertical in two parallel groups which are usually at right angles to each other. It is these joints which result, when weathered, in the characteristic rectangular or square blocks in karst limestone pavements. Joint densities were found to be highly variable and related not to limestone bed thickness, but rather to the internal structure of the limestone, with coarser rocks tending to have most joints. No direct connection between joint type, density and degree of solution enlargement was made by Doughty but it is probable that conjugate joints, having laterally extensive interconnection be more prone to solution enlargement, together with low angle joints (considered to be associated with faulting).

Rates of travel of groundwaters through conduits are highly variable but have been estimated at a few locations by the use of tracer tests. In the Malham area, flow velocities have been measured at about 240 m/d (Carter and Cash, 1900) to over 9600 m/d in 1972 and up to 4800 m/d in 1973 (Smith and Atkinson, 1977), the differences being attributed by the latter to variations in rainfall. Smith and Atkinson also considered the complex interconnections

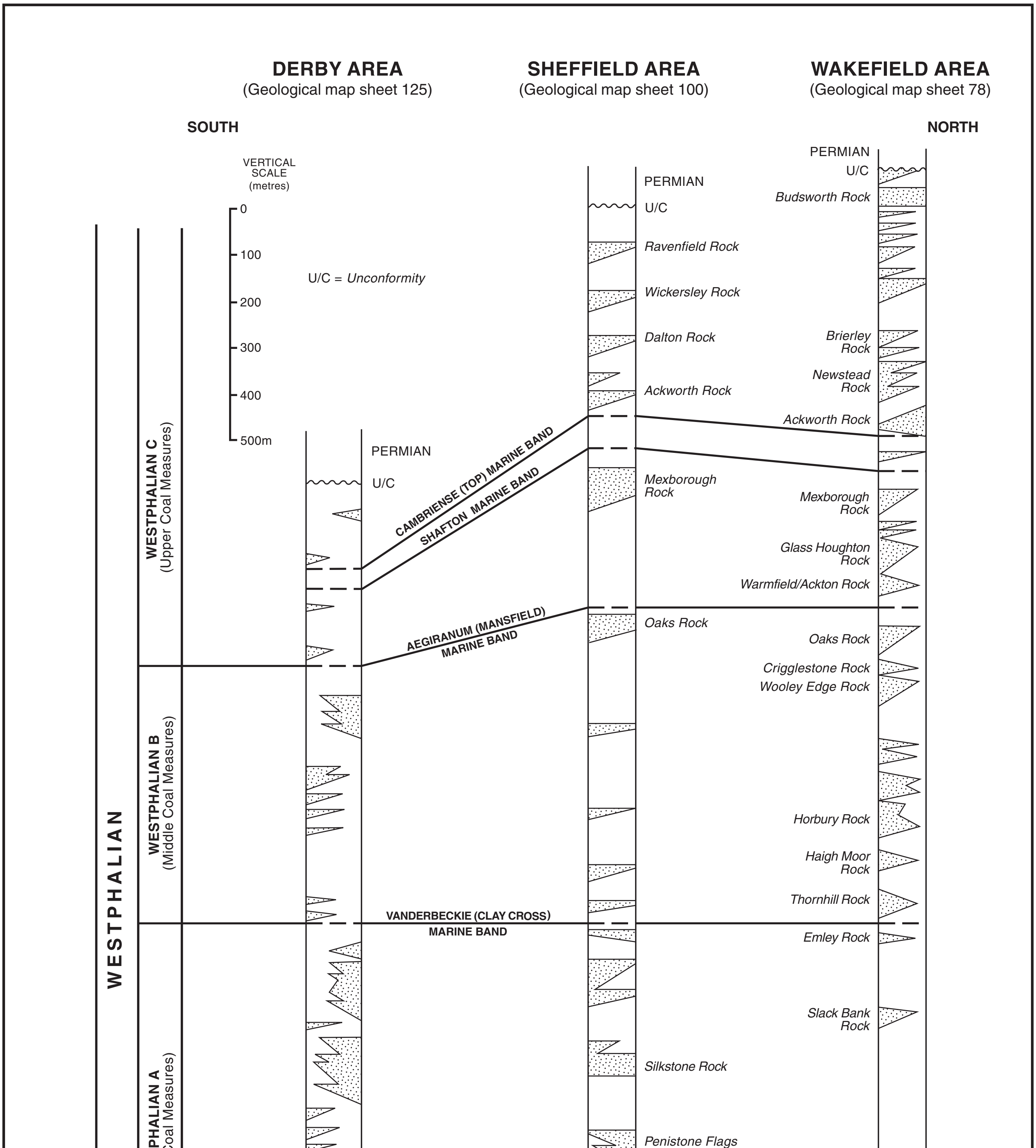


Figure 8.22 Westphalian stratigraphy to the east of the Pennines (Yorkshire and East Midlands coalfields).

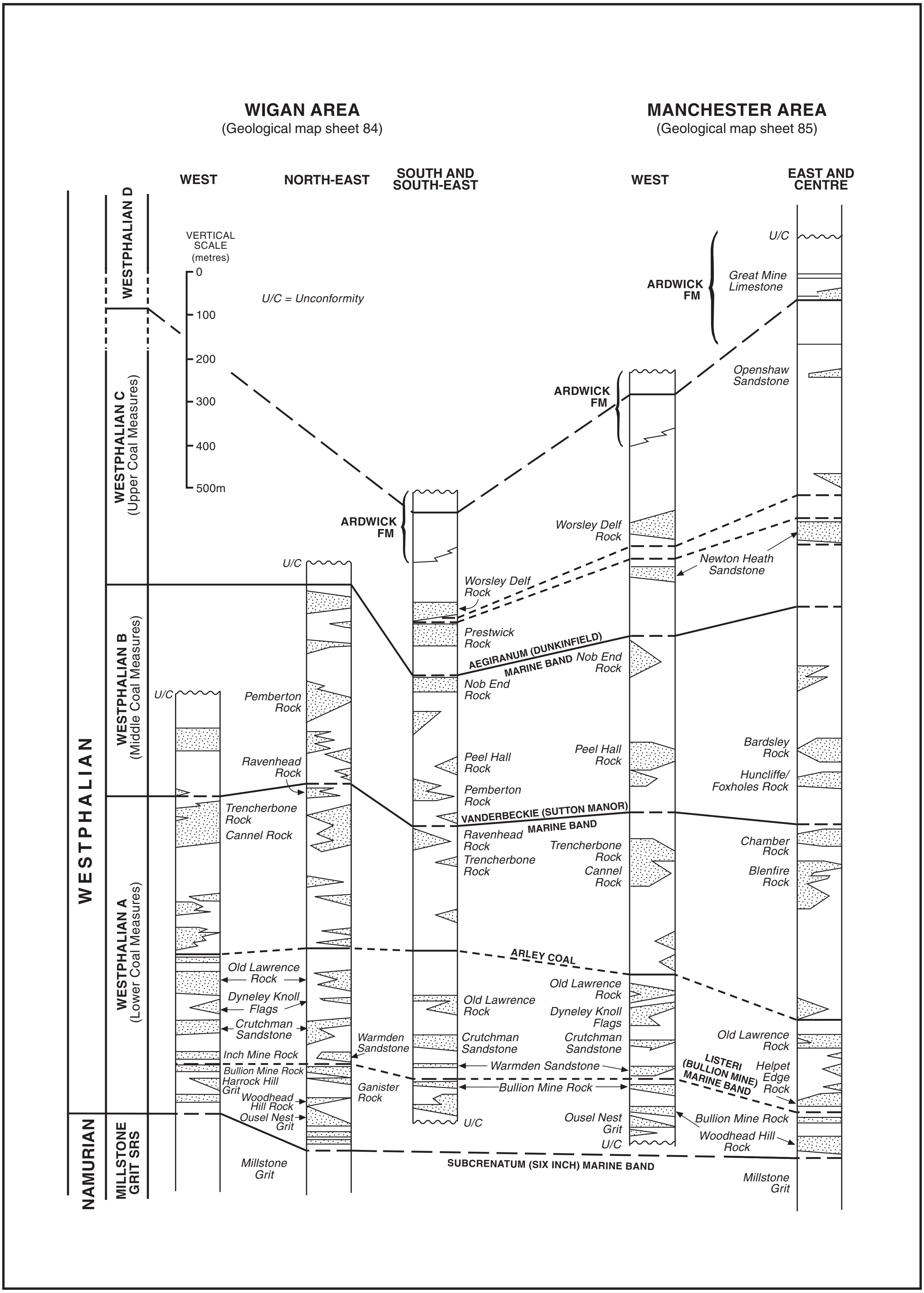


Figure 8.23 Westphalian stratigraphy to the west of the Pennines (Lancashire Coalfield).

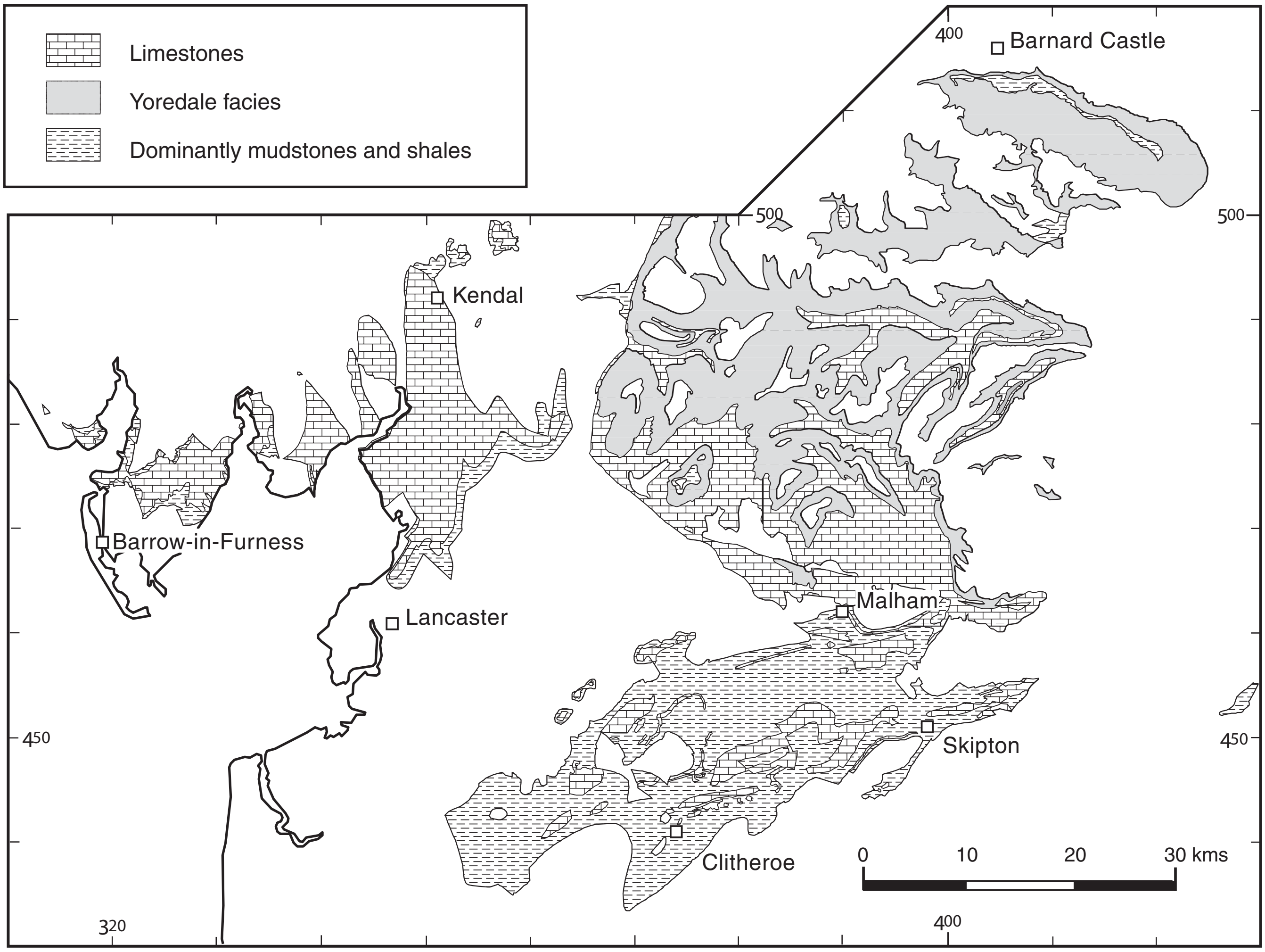


Figure 8.24 Distribution of the outcrops of various Carboniferous Limestone lithologies.

between sinks and points of discharge in some detail. Carter and Cash (1904) estimated rates of travel in the Ingleborough area as varying between 120 and 336 m/d the variation again being ascribed to rainfall effects.

Borehole yields are highly variable; very productive if large conduits are intersected but low yielding or occasionally completely dry if no joints or fractures are encountered. The density and size of fractures commonly decrease rapidly with depth, giving an effective aquifer thickness of only 50 to 80 m although the actual thickness of the formation may be significantly greater. The unpredictability of the aquifer and, to a lesser extent, the fact that the Carboniferous Limestones underlie extensive tracts of sparsely populated uplands which are well supplied with surface waters, has militated against the drilling of boreholes to exploit groundwater resources. Borehole yields in the northern Pennines, from the limited information available, are very variable, ranging from only a few m^3/d to (exceptionally) almost 14 400 m^3/d. Very low yielding and dry boreholes, which would not have been tested, are however by no means uncommon. Where successful, the majority of well yields lie in the range 240 to 1920 m^3/d.

Occasional attempts to improve yields by a variety of development methods appear to have met with little success. At Kettlewell [SD 9746 7254] for example, an initial yield of 19.2 m^3/d, obtained from a 200 mm diameter, 85 m deep borehole, was only improved to 30 m^3/d following the use of explosives and further to 36 m^3/d following treatment with acid (Aldrick, 1977).

Boreholes in close proximity can often produce very different yields if water-bearing fractures are encountered in some boreholes but not others. At Bellerby [SE 109 929], yields of 2160 m^3/d (from a well with two boreholes in its base) and of 864 and 984 m^3/d were obtained from boreholes penetrating the Carboniferous Limestone Yoredale facies, in addition to a dry borehole (Aldrick, 1977).

Namurian

The Millstone Grit constitutes a multilayered aquifer in which the thick, massive grit and sandstone horizons effectively act as separate aquifers with the intervening mudstones and shales acting as aquicludes or aquitards. The more important aquifer horizons include the Pendle, Wosley Wise, Todmorton, Kinderscout, Chatsworth, Ashover, and Middle grits, the Rough Rock, and their lateral equivalents.

Groundwater storage and movement in the well-cemented grits and sandstones is predominantly through joints and fractures with only minor contributions from the rock matrix. Borehole yields are dependent on the number and size of fractures encountered in a productive horizon. Many boreholes penetrate more than one such horizon. During construction of the Bowland Forest Tunnel initially high flow rates encountered from fractured zones declined with time and at depths exceeding about 200 m, inflow was generally insignificant (Earp, 1955). This may indicate that, in some areas at least, there is a maximum depth to which the beneficial effects of fractures extend.

The groundwater potential of the main water-bearing horizons is very variable and some horizons may only be of local importance. Yields are in consequence highly variable even over short distances but tend to be greatest in the north and central parts of the area, reducing southwards due to attenuation of the water bearing horizons. Borehole yields from the Millstone Grit as a whole, range from 432 to 864 m^3/d but under particularly favourable conditions may range up to 4320 m^3/d. Boreholes are often artesian. Initial yields are not however always sustainable, sometimes declining with time as storage is depleted by pumping. Abundant springs are frequently located at junctions between sandstone and shale horizons, some of which are used for public supply (Institute of Geological Sciences, 1982b).

The Pendle Grit provides significant yields in the Earley area as does the Guiseley Grit in the vicinity of Guiseley (Institute of Geological Sciences, 1982b). The Huddersfield White Rock is a very good aquifer underlying, and to the south of, Huddersfield but yields decline rapidly to the east as the sandstone thins. Yields of over 2400 m^3/d have been recorded from the Huddersfield White Rock in the Aire and Calder valleys. It is the most important aquifer horizon in the Don and Dearne catchments, where yields of up to 1680 m^3/d from boreholes and 144 m^3/d from springs, have been recorded (Gray et al., 1969).

Yields of up to 552 m^3/d have been obtained from the Kinderscout Grit in the Aire and Calder catchments but further north yields of up to 2160 m^3/d have been recorded (Gray et al., 1969). Further to the south, the outcrop is too limited to be of great importance although the Ladybower Reservoir—Rivelin Dam Tunnel (7.2 km in length) receives an inflow of about 2280 m^3/d from the Kinderscout Grit (Eden et al., 1957). To the north of the River Aire, yields of up to 1080 m^3/d have been recorded for the Middleton Grit. Up to 432 m^3/d has been obtained from the Skipton Moor Grit where the sandstones are at their maximum thickness but marked lithological variations make predictions of yield for this horizon difficult (Gray et al., 1969).

The Rough Rock is arguably the most consistent aquifer horizon, being tapped by numerous boreholes across the area. Particularly good yields (960 to 2640 m^3/d) are obtained in the Bradford area and to the east of Halifax. In contrast, to the north of Glossop where the Rough Rock is unusually dense and lacking in fractures, yields are commonly very low (Gray et al., 1969). There is a general trend of decreasing yield with increasing depth to the aquifer horizon, varying from over 4800 m^3/d beneath 24 m of Coal Measures overburden to 144 m^3/d beneath 170 m of overburden (Gray et al., 1969).

Although it is often stated that the individual sandstone or grit horizons of the Millstone Grit act as effectively separate aquifers, few well documented examples in fact exist. One such is the trial borehole constructed at North Valley, Colne [SD 8873 4030], which penetrated an unnamed sandstone horizon positioned above the Revidge Grit. Two nearby older supply boreholes, at Glenmills and Stonebridge, penetrated to the underlying Revidge Grit, having been constructed to case out the shallower sandstone horizon. During aquifer testing in the North Valley Borehole, water levels in the other two wells showed no response and the Stonebridge Borehole remained artesian. It is also notable that the pumped and recovery levels recorded in the North Valley Borehole during a twelve month monitoring period showed a gradual decline (of 4.7 m from rest water level). This indicates a steady depletion of storage in the sandstone horizon from which abstraction was occurring (Seymour, 1980).

Similar effects were observed during testing of a borehole which penetrated the Roaches Grit at Dawson Barn Farm [SJ 9685 7640]. The initial pumping rate was between 26.4 and 33.6 m^3/d for eight hours per day but was by necessity dramatically reduced after six days when the pumping water level fell to the pump level. This had been preceded by a gradual fall in pumped water levels combined with incomplete recovery. It became apparent that pumping in excess of 3.6 m^3/d for three hours per day depleted aquifer storage rather than exploiting direct recharge (Seymour, 1979).

Reductions in transmissivity and yield were also observed during testing at Corn Close Abstraction Borehole No.2 [SD 9428 4116], which penetrated 41 m of the Rough Rock. A pumping test was initially carried out in 1980, when step testing showed a reduction in transmissivity from 1605 to 267 m^2/d, as discharge rates increased from 10 320 to a maximum of 88 800 m^3/d. Transmissivity again decreased as the constant rate test progressed and was considered to be a function of the limited storage of the Rough Rock aquifer. Testing was again carried out in 1985, primarily to determine if declining yields were due to clogging of borehole screens by chemical/ bacterial action, to rusting, or to a reduction in saturated aquifer thickness associated with falling water levels. Step testing indicated that borehole efficiency had not altered substantially, ruling out clogging of the screens or rusting as a cause. There had however been a marked fall in rest water level of about 10 m over the period. It was concluded that the reduction in yield between 1980 and 1985 had been caused by a reduction in saturated aquifer thickness (North West Water Authority, 1981 and 1986).

The precipitation of iron oxides on borehole screens is occasionally quoted as a possible cause of yield reductions, but has only been documented for one site. At Hallicombes Farm, Sutton [SJ 9551 7083], a borehole penetrating the Roaches Grit yielded about 168 m^3/d when initially tested in October 1981. For a subsequent test in June 1982 to establish the effect of abstraction on nearby springs during a period of dry weather, the discharge rate had to be reduced to 6 m^3/d. The discharge water was visibly discoloured and analyses showed a higher iron content. It was therefore concluded that the reduction in yield was due to clogging of fractures in the borehole area or of clogging of the pump by iron oxide precipitates (North West Water Authority, 1982).

Little is known regarding the aquifer properties of the mudstones and shales which constitute a significant portion of the Millstone Grit succession, although Wagstaff (1991) considered that the intergranular hydraulic conductivity of these horizons would be very much less than 0.1 m/d. Fracture systems do exist in the strata and, although they tend to be less frequent and of narrower aperture than in the sandstones, they could provide a means for water movement.

A tracer test carried out at Marywells Quarry, Cullingworth near Bradford showed the tracer to have travelled about 500 m to springs from the injection point over a period of less than two days. In addition the direction of flow was different to that suggested by the monitoring of water levels, indicating that groundwater flow was primarily by fracture flow (Townend and Aldridge, 1996).

Westphalian

The Coal Measures Group form a complex multilayered minor aquifer. Argillaceous strata predominate, acting as aquitards or aquicludes, isolating the occasional thicker sandstone horizons which effectively act as separate aquifers. Coal Measures sandstones are generally fine grained, very well cemented, extremely hard and dense and in consequence possess very little primary porosity or intergranular permeability. Groundwater storage and movement occurs predominantly within and through fractures in the sandstones. Under natural conditions the sandstones act as individual aquifers separated by the intervening impermeable argillaceous horizons and constitute a complex multi-layered aquifer. Sandstone horizons tend to be thickest and most numerous to the west of the Pennines where they constitute up to a third of the succession (Ministry of Housing and Local Government, 1964). To the east of the Pennines sandstones generally constitute no more than 25% of the succession (Holliday, 1986) and tend to thin and become less common in the south.

To the east of the Pennines the lateral extent of sandstone horizons is only rarely greater than 150 km^2, commonly thinning to the east of the outcrop area (Gray et al., 1969; Rae, 1978b). Although jointing is frequently present in sandstone horizons their interconnection is often poor and sandstones at depth can be dry despite the presence of joints (Holliday, 1986). Rae (1978b) considered that they were generally unlikely to yield significant amounts of water at depths of more than 200 m due to this effect. The reduction in permeability is compounded by decreases in primary porosity and intergranular permeability with depth, due to increased cementation, an increased weight of overburden and compaction (Gray et al., 1969). In the southern part of the coalfields folding would appear to have a greater influence on permeability, creating open joints in anticlinal areas which permit water to infiltrate and migrate to synclinal areas, (Holliday, 1986). This resulted in the Derbyshire pits being the wettest in England largely due to their location in synclinal belts (Frost and Smart, 1979). Deeper workings in the concealed part of the Coalfield to the east are generally drier due to overlying impermeable Permian marls which severely restrict infiltration, as well as the reduction in intergranular and joint permeability associated with increasing depth (Frost and Smart, 1979).

Mine drainage in the Yorkshire Coalfield in 1972 totalled 178 000 m^3/d from 96 active and 104 disused mines. In the coalfield as a whole about 50% of mines discharge at rates of less than 2592 m^3/d (Rae, 1978a). In comparison, mine drainage in the East Midlands Coalfield, totalled 41 000 m^3/d, from 47 mines (37 active and eight disused) in 1972 (Rae, 1978a). Total mine drainage abstraction from the Lancashire Coalfield was about 38 200 m^3/d (around 1600 m^3/h) in 1961 (Ministry of Housing and Local Government, 1964). Pumping for mine drainage has declined dramatically in recent years with the closure of numerous mines.

Sandstone outcrop areas are generally small, limiting the amount of recharge which can infiltrate to individual sandstone units. Extensive faulting, particularly in the northern sections of the coalfields, has frequently split previously continuous sandstone horizons into disconnected isolated fault-bounded blocks, to which no direct recharge can occur. Initially high yields frequently decline substantially due to the depletion of aquifer storage by abstraction.

The mining of numerous coal seams has been widespread over virtually the whole of the Lancashire, Yorkshire and East Midlands coalfields. The widespread removal of coal has largely disrupted natural hydrogeological conditions of the Coal Measures Group by the creation of open shafts, roadways and galleries, as well as collapsed, disused workings and by producing subsidence-induced fractures. Many mine drainage adits (soughs) continue to drain the Coal Measures long after the mines have been abandoned (Cheney et al., 1999). These features have created hydraulic continuity between layers which were previously isolated and, in some places, between aquifer horizon and flooded disused workings. This modification of hydrogeological conditions was sufficiently extensive for Banks (1997) to consider the Coal Measures Group to be ‘an anthropogenically enhanced aquifer’. The early widespread development of coal mining and attendant mine drainage pumping is likely to have made development of groundwater resources in the Coal Measures difficult due to the lowering of water levels, and widespread contamination from the mining process itself and associated industrial activities. In addition large quantities of water were readily available for industrial use from pumped mine drainage. Water supply wells and boreholes are not therefore generally numerous.

To the east of the Pennines, sandstone horizons in the Lower and Middle Coal Measures are generally thinner and drier than those of the Upper Coal Measures (Rae, 1978b). In the East Midlands Coalfield, the Wingfield Flags and Cranshaw Sandstone, (near the base of the Lower and Middle Coal Measures sequence), are relatively widely developed whilst the Woolley Edge and Oaks Rocks are also important water bearing horizons. Yields are markedly variable but up to 960 m^3/d is typical at outcrop (Institute of Geological Sciences, 1981). Further north, in the Yorkshire Coalfield, the Elland Flags and Thornhill Rock are of particular importance but the Oaks and Woodley Edge Rocks again constitute important Lower and Middle Coal Measures aquifer horizons (Institute of Geological Sciences, 1982b). In the Bradford area, the Elland Flags are by far the largest source of groundwater, exceeding the quantities obtained from the Millstone Grit Rough Rock and Huddersfield White Rock, mainly due to their great thickness (Waters et al., 1996). In the Upper Coal Measures, the Ravensfield, Wickersley, Ackworth rocks and particularly the Mexborough Rock are important aquifer horizons (Institute of Geological Sciences, 1981). The sandstones commonly have a limited lateral extent, for example, the Mexborough Rock is limited in extent to South Yorkshire and Nottinghamshire. Yields from the Coal Measures Group in the Yorkshire Coalfield range up to 3840 m^3/d with a mean of 864 m^3/d but about 60% of yields lie in the range of 72 to 696 m^3/d (Rae, 1978b). There was no detectable relationship between borehole yield and diameter. Initial good yields, including artesian overflows, often decline significantly with time.

To the west of the Pennines the most important water-bearing sandstones are the Old Laurence and Woodhead Hill rocks (Ministry of Housing and Local Government, 1964) but also include the Worsley Delf, Pemberton, Rowenhead and Trencherbone rocks and Crutchman Sandstone (Forster et al., 1995). Whilst mining was widespread, many sandstones drained into the workings, which were pumped to maintain dry working conditions. With the closure of the majority of mines in the exposed section of the Coalfield during the 1960s and the remaining mines in the concealed section in the 1990s, pumping ceased. Water levels in the Coal Measures have risen rapidly following the cessation of pumping but can never return to their original levels due to the presence of shafts, galleries, extensive soughs and fracturing associated with subsidence (Cheney et al., 1999). In the Wigan area, yields from boreholes up to 300 mm diameter generally range from 432 to 864 m^3/d, whilst large diameter mine shafts may occasionally exceed 1680 m^3/d (Forster et al., 1995). The Upper Coal Measures to the west of the Pennines would not normally be expected to yield more than about 432 m^3/d (Ministry of Housing and Local Government 1964).

Much higher yields are obtained from boreholes penetrating flooded disused workings in coalfields on either side of the Pennines, although frequently water quality is poorer.

8.6.2.2 *Core data*

Dinantian

Laboratory measurements of porosity are available for Carboniferous Limestone samples from four outcrop locations and three boreholes in the area. Average porosity for the outcrop samples was 1.3% and for borehole samples 1%. No permeability measurements are available.

Holliday (1986) quoted an average permeability of about 0.14 m/d (240 mD) for samples obtained from a 23 m section of limestones at a depth of over 180 m in a borehole located near Burnley.

Namurian

In the East Midlands the permeability of the Millstone Grit sandstones was considered by Downing and Howitt (1969) to be quite variable, averaging only a few tens of millidarcies and with porosities generally ranging between 10 and 20%.

The BGS Aquifer Properties Database contains porosity and intergranular permeability measurements from 16 outcrop localities in the Pennines area. Porosity values range from 6 to 23%, with arithmetic mean and median values of about 14%. Permeability values range from 3×10^{-4} to 0.7 m/d (0.7 to 1061 mD), with arithmetic mean and median values of 5×10^{-3} to 4×10^{-2} m/d (10 and 66 mD). These values, obtained from samples of weathered outcrops are likely to be higher than those applicable to unweathered strata at depth.

Flow in the Millstone Grit aquifers tend to decrease rapidly with depth and sandstones which are soft and decalcified at outcrop are commonly well cemented, hard and compact down-dip. At depth in the East Midlands the Namurian sandstones are oil and gas reservoirs. The results from a large number of drill-stem tests in the East Midlands oilfields shows that there is a general trend towards lower values in a northerly direction, with porosity decreasing from 26% near Newark to between 7 and 11% in the Gainsborough area, and permeability reducing from about 0.015 m/d (30 mD) to about 4×10^{-4} m/d (1 mD) (mean 6.8×10^{-3} m/d) in the north (Holliday, 1986). It is not known whether a similar trend exists in the Millstone Grit area of the west Pennines.

Westphalian

The properties of the Coal Measures sandstone aquifer horizons were considered by Downing and Howitt (1969), to be generally more variable than those of the Millstone Grit, with permeabilities ranging up to only 0.01 m/d (20 mD) and porosity values generally ranging from 5 to 15%.

Table 8.10 contains a summary of porosity and intergranular permeability measurements available from the BGS Aquifer Properties Database for the Coal Measures Group in the Pennines area. Both outcrop and borehole samples are likely to represent sandstone horizons within the Coal Measures. The number of sites in each category from which samples were obtained are small, ranging between one and six locations. It should be noted that for the Middle Coal Measures of the east Pennines where it would appear that samples were obtained from six borehole locations, four of these boreholes were in fact located in close proximity within a single quarry area. As may be expected values of both porosity and permeability are greater for outcrop samples than borehole samples, this

Table 8.10 Summary of porosity and permeability data for the Coal Measures Group in the Pennines area.

AREA	**WEST PENNINES**			**EAST PENNINES**			
Aquifer	**Lower Coal Measures**	**Middle Coal Measures**		**Lower Coal Measures**	**Middle Coal Measures**		**Upper Coal Measures**
Sample type	Outcrop	Outcrop	Borehole	Borehole	Outcrop	Borehole	Borehole
Porosity (%)							
No. sites	5	3	3	1	5	6	3
No. values	17	9	44	57	21	296	76
Minimum	9	12	2	8	15	0.7	3
Maximum	30	24	21	13	19	21	31
Arithmetic mean	15	18	9	11	17	11	13
Median	11	-	9	11	18	11	10
Permeability (m/d)							
No. sites	5	3	3	1	5	6	3
No. values	17	7	44	57	21	296	76
Minimum	6.4×10^{-4}	—	6.4×10^{-6}	3.8×10^{-5}	4×10^{-4}	6.4×10^{-6}	6.4×10^{-6}
Maximum	3.7	—	3×10^{-1}	9.4×10^{-4}	4×10^{-2}	1.7×10^{-2}	1.7×10^{1}
Arithmetic mean	4.2×10^{-1}	—	1.1×10^{-2}	2×10^{-4}	5.7×10^{-3}	5.8×10^{-4}	4×10^{-1}
Median	1.4×10^{-3}	—	5.3×10^{-5}	1.5×10^{-4}	6.4×10^{-4}	1.3×10^{-4}	4.7×10^{-4}

reflecting of the weathered nature of the former. The data contained in Table 8.10 suggest that although borehole sample porosities in the Middle Coal Measures to the east and west of the Pennines are reasonably similar, the permeabilities in the west Pennines are, on average, higher. Similarly there is a suggestion that primary porosities and intergranular permeabilities of borehole samples from the Upper Coal Measures are generally higher than those from the Middle Coal Measures. The data set is, however, small.

In the concealed section of the coalfields to the east of the Pennines, the Coal Measures sandstones constitute major oil field reservoirs and in consequence their aquifer properties have been more frequently determined than in the outcrop area. Porosity values have been determined from geophysical logs and laboratory core measurements whilst permeability has been determined from core analyses and drill stem tests, the latter being more representative of the aquifer as a whole since the bulk permeability is measured rather than just the intergranular permeability. Measurements from these sources provided a mean porosity range, for Lower and Middle Coal Measures sandstones, of 7% to 20% with a predominance of values at about 12%. Permeability values ranged from 2.1×10^{-5} to 0.019 m/d (0.06 to 37 mD) with a mean of about 6.3×10^{-3} m/d (13 mD) but locally exceptional values of up to 0.24 m/d (400 mD) have been recorded. Upper Coal Measures sandstones porosities range from 12 to 19% with a mean of about 15%. Permeabilities typically range from 8.7×10^{-4} to 0.09 m/d (2 to 160 mD) with a mean of about 0.032 m/d (60 mD). These values are biased towards sandstones with a potentially high permeability, since no testing would normally be carried out on tighter sandstones which can be identified by geophysical log interpretation (Holliday, 1986). At outcrop in the Yorkshire Coalfield intergranular permeabilities of sandstones are invariably less than 0.02 m/d and generally much less (Rae, 1978b).

8.6.2.3 *Pumping test results*

Dinantian

The distribution of boreholes which penetrate the Carboniferous Limestone is sparse at best and diminishes in a northerly direction, with very few if any located in the northernmost part of the area. Only basic yield and drawdown measurements are generally available since formal pumping tests, which would permit the determination of transmissivity values, have only been carried out at a few sites.

TRANSMISSIVITY AND STORAGE COEFFICIENT

There are 19 transmissivity values available for the Carboniferous Limestone in the area, ranging from 0.1 to 1015 m^2/d. The upper, extreme, value is the result of a very high pumping rate and minimal drawdown. The interquartile range is 1.6 to 43 m^2/d. The arithmetic and geometric means are 153 and 13 m^2/d, and the median is 18 m^2/d. Apart from the single high value, the range is surprisingly small given the degree of aquifer variability, but the dataset is small.

Only a single storage coefficient is available in the area (3×10^{-4}). The lack of storage coefficients is a reflection of the lack of observation boreholes.

SPECIFIC CAPACITY

Intuitively it might be expected that yields and specific capacity would be lower in areas underlain by Yoredale facies, where mudstones and shales are dominant, and higher in areas where limestones are dominant (Figure 8.24). However, an examination of available data has not shown any positive correlation between either yield or specific capacity and lithology, although this may be due, at least in part, to the scarcity of the data.

A total of 54 specific capacity records are available, with values ranging from 0.35 $m^3/d/m$ to an extreme value of over 1900 $m^3/d/m$. The 25/75 percentile range is 3 to 46 $m^3/d/m$; again a surprisingly narrow range given the high degree of aquifer variability (Figure 8.25). The arithmetic and geometric means are 91 and 12 $m^3/d/m$, the median 11 $m^3/d/m$ and an interquartile range of 42 $m^3/d/m$.

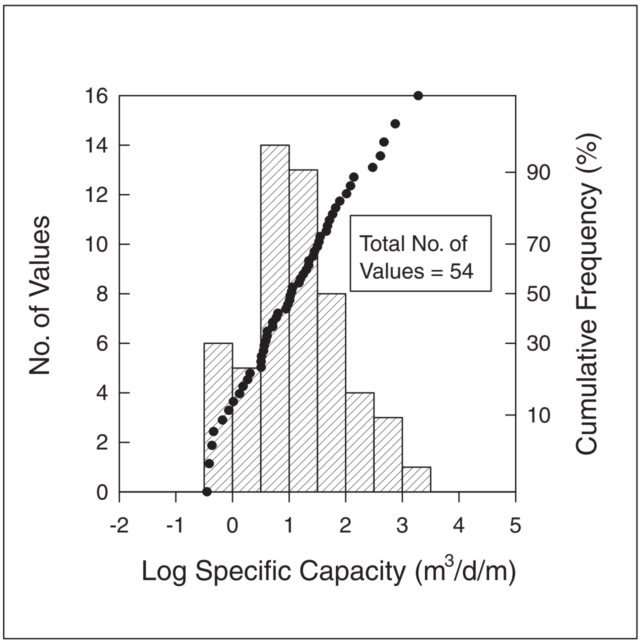


Figure 8.25 Distribution of specific capacity data from pumping tests in the Carboniferous Limestone of the Pennines.

Namurian

The greatest concentrations of sites are on the margins of the outcrop, with clusters in the Bradford and Keighley areas and approximately along the line of the River Lune to the north-east of Lancaster. Sites are sparsely distributed to the north of Leeds.

A summary of the aquifer properties values for the Namurian Millstone Grit in the Pennines area is presented in Table 8.11 whilst distribution histograms and cumulative frequency plots of transmissivities and specific capacity are shown in Figures 8.26 and Figure 8.27 respectively.

Particular grit horizons are specified for very few of the sites, probably because faulting often makes the identification of a particular horizon difficult and many boreholes penetrate more than one horizon. Grit horizons are named for only 20 sites, namely the Ashover Grit and Huddersfield White Rock (one site each), the Kinderscout Grit (four sites), Pendle Grit (two sites), Revidge Grit (five sites) and the Rough Rock (seven sites).

TRANSMISSIVITY AND STORAGE COEFFICIENT

In view of the highly variable nature of the Millstone Grit aquifer and the interrelationship between the number and size of water bearing fractures and yield, transmissivity values are likely to vary significantly even over relatively short distances.

Table 8.11 Summary of aquifer properties data for the Millstone Grit in the Pennines area.

Millstone Grit of the Pennines		
Number of transmissivity records	81	—
Minimum/maximum transmissivity value (m^2/d)	0.6	1059
Arithmetic/geometric mean of transmissivity (m^2/d)	93	25
Median/interquartile range of transmissivity (m^2/d)	26	73
25/75 percentile of transmissivity (m^2/d)	7	80
Number of storage coefficient records	3	—
Maximum/minimum storage coefficient values	1.3×10^{-2}	1×10^{-4}
Number of specific capacity records	123	—
Minimum/maximum specific capacity (m^3/d/m)	0.54	9092
Arithmetic/geometric mean of specific capacity (m^3/d/m)	140	23
Median/interquartile range of specific capacity (m^3/d/m)	21	67
25/75 percentile range of specific capacity (m^3/d/m)	8	76

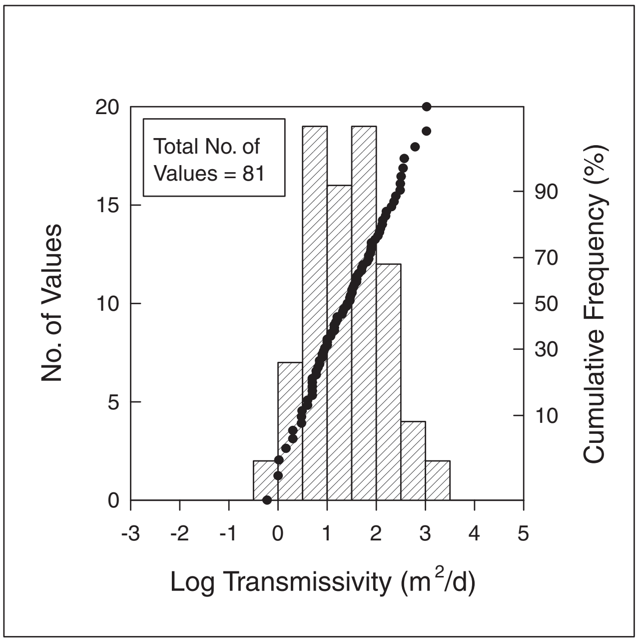


Figure 8.26 Distribution of transmissivity data from pumping tests in the Millstone Grit of the Pennines.

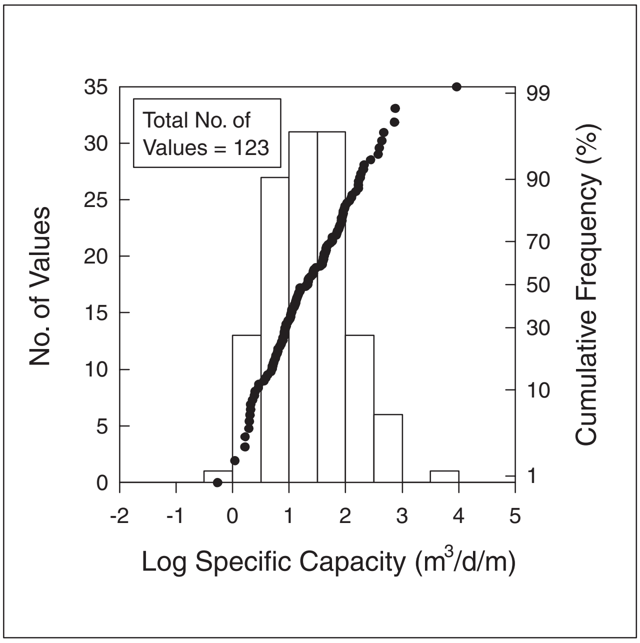


Figure 8.27 Distribution of specific capacity data from pumping tests in the Millstone Grit of the Pennines.

This is well illustrated by three boreholes at Tong Park Mills, Basildon [BH1 at SE 1693 4019, BH2 at SE 1625 4048 and BH3 at SE 1660 4068] all of which penetrated the Rough Rock at outcrop and the Huddersfield White Rock, Guiseley Grit and Woodhouse Grit at depth. The discharge rate during the constant rate test on Borehole 1 averaged 1625 m^3/d with a drawdown of 8.67 m after 24 hours but was still declining at a rate of 5 cm per hour. This response, sometimes termed drawdown creep, is fairly typical of Millstone Grit abstractions, and is commonly ascribed to depletion of storage over time. Transmissivity values declined over the period of the test, to a minimum of 74 m^2/d but even this is probably an overestimate. Borehole 2 was tested at a discharge rate of 768 m^3/d and the water level stabilised after only one hour with 17.4 m of drawdown, providing a transmissivity value of 57 m^2/d. Borehole 3 was tested at an average discharge rate of 2016 m^3/d, producing a drawdown of 4.67 m which stabilised after only two minutes, falling only a further 0.05 m over the following 24 hours. A transmissivity of 504 m^2/d was calculated using a steady state approximation.

Very similar transmissivity values can however sometimes be obtained from boreholes in close proximity. Two boreholes at Silsden [at SE 0499 4821 and SE 0498 4825] of 123 and 150 m depth respectively and 150 mm diameter, both penetrated the Nesfield Sandstone at outcrop with Marchup or Almscliffe grits at depth. Cooper-Jacob and steady state analyses, produced transmissivity values in the very narrow range of 9.8 to 32.7 m^2/d.

Three storage coefficients are available, two of which are indicative of confined conditions whilst the third is in the unconfined range.

Specific capacity

The maximum specific capacity of more than 9000 m^3/d/m is distinctly anomalous, with only two other values exceeding 700 m^3/d/m and the rest less than 560 m^3/d/m.

Where particular grit horizons have been named, they fall within the interquartile range (25/75%) with the exception of only two sites; one in the Revidge Grit (specific capacity 728 m^3/d/m and transmissivity 354 m^2/d) and one in the Rough Rock (transmissivity 692 m^2/d). There would appear to be no discernible geographic distribution of yield, specific capacity or transmissivity.

Forty four specific capacity values are available with corresponding transmissivity values. A plot of these values (Figure 8.28) shows a rather poor relationship between the two parameters for the Millstone Grit.

Westphalian

There is a much greater concentration of sites located in the Lancashire Coalfield to the west of the Pennines than in the east Pennines. Within the coalfield the majority of sites are located in the southern part, (in the St Helens/Wigan/Bolton/ Manchester area). A particularly dense cluster of sites is located in the Wigan/Bolton area. To the east of the Pennines, the majority of the sites are positioned in the north Yorkshire section of the coalfield with fewer sites in the East Midlands Coalfield. Two lower yielding sites are located in the small Ingleton coalfield.

A summary of the aquifer properties data for the Coal Measures Group for the areas to the west and east of the Pennines is presented in Table 8.12.

Distribution histograms and cumulative frequency plots of transmissivity and specific capacity for the Coal Measures Group outcrop to the east of the Pennines are shown in Figures 8.29 and 8.30 respectively. A similar plot for the specific capacity data for the area to the west of the Pennines is shown in Figure 8.31 but, strikingly, there are no transmissivities available for this area.

TRANSMISSIVITY AND STORAGE COEFFICIENT

Despite the much greater density of sites to the west of the Pennines there are no transmissivity or storage coefficients available. Both specific capacities and transmissivities are concentrated geographically in the northern section of the Coal Measures Group outcrop.

There are few published references on the aquifer properties of the Westphalian strata of the Pennines. Banks (1997) provided a range of transmissivities of 4 to 40 m^2/d for the Coal Measures in the north Derbyshire/South Yorkshire section of the coalfields. Calculated transmissivity values

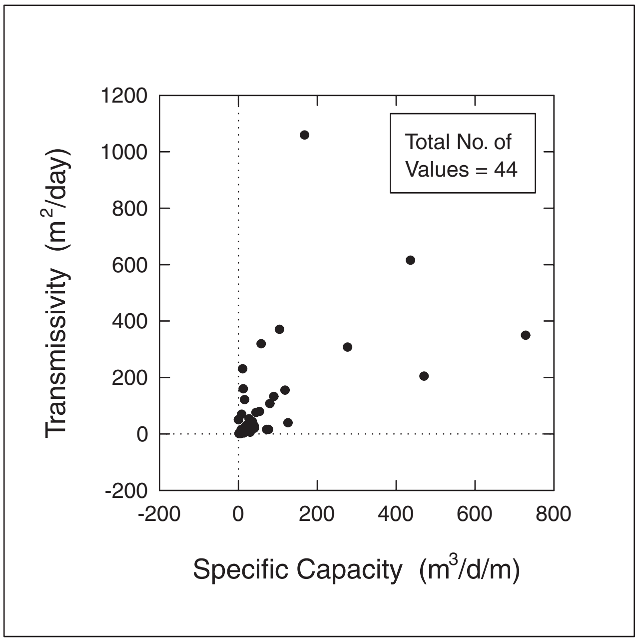


Figure 8.28 Correlation between specific capacity and transmissivity for the Millstone Grit of the Pennines.

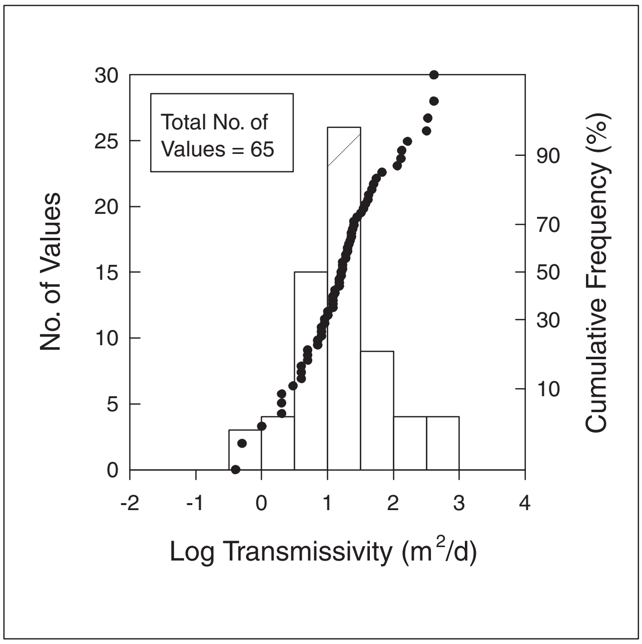


Figure 8.29 Distribution of transmissivity data from pumping tests in the Coal Measures Group for the area to the east of the Pennines.

Table 8.12 Summary of aquifer properties data for the Coal Measures Group for the areas to the west and east of the Pennines.

Coal Measures Group	West Pennines		East Pennines	
Number of transmissivity records	—	—	65	—
Minimum/maximum transmissivity value (m^2/d)	—	—	0.4	413
Arithmetic/geometric mean of transmissivity (m^2/d)	—	—	46	16
Median/interquartile range of transmissivity (m^2/d)	—	—	16	25
25/75 percentile of transmissivity (m^2/d)	—	—	8	33
Number of storage coefficient records	—	—	1	—
Storage coefficient value	—	—	3.4×10^{-5}	—
Number of specific capacity records	95	—	27	—
Minimum/maximum specific capacity (m^3/d/m)	0.3	19093	2.2	4912
Arithmetic/geometric mean of specific capacity (m^3/d/m)	578	32	302	34
Median/interquartile range of specific capacity (m^3/d/m)	28	95	21	103
25/75 percentile of specific capacity (m^3/d/m)	8	104	9	112

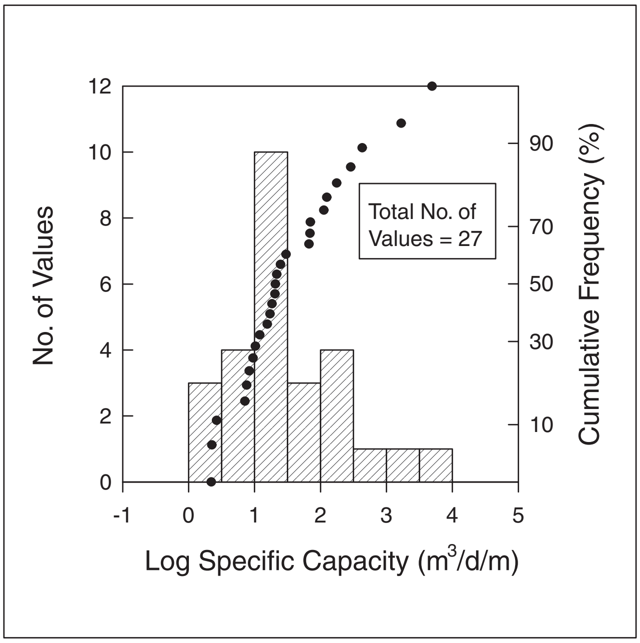


Figure 8.30 Distribution of specific capacity data from pumping tests in the Coal Measures Group for the area to the east of the Pennines.

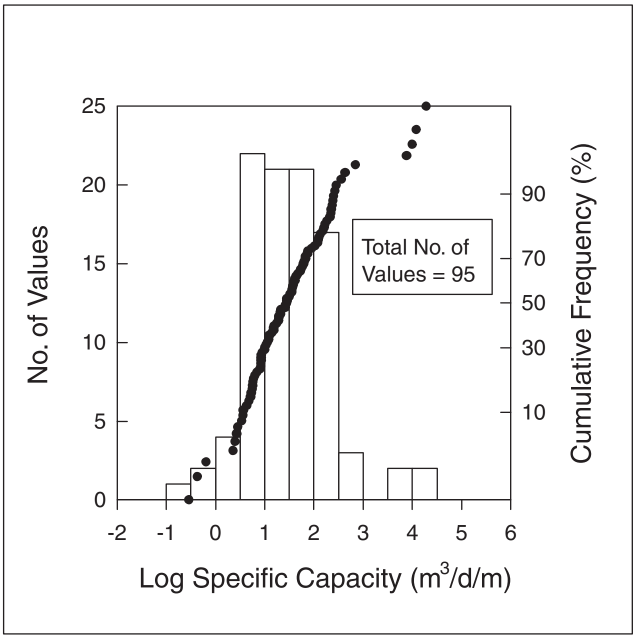


Figure 8.31 Distribution of specific capacity data from pumping tests in the Coal Measures Group for the area to the west of the Pennines.

for bailing tests and pumping tests on ten boreholes penetrating the Elland Flags in the Bradford area provided an average value of 204 m^2/d (Waters et al., 1996).

There are problems analysing pumping test data for transmissivity from boreholes penetrating the Coal Measures Group strata. Following an initial period of fairly rapid drawdown on commencement of pumping the rate of drawdown decreases, but instead of reaching equilibrium continues to decline at a slow but steady rate for as long as pumping continues. This effect, sometimes termed drawdown creep, was noted during the testing of boreholes penetrating the Coal Measures at Dewsbury [SE 226 224], Swillington Common [SE 3770 3284] and Denby Dale [SE 2220 0827]. Transmissivity values calculated for the earlier stages of the test are invariably higher (sometimes substantially so), than those for the late stages. One interpretation is that the effect is caused by depletion of aquifer storage whilst pumping at too high a discharge rate. Alternatively, it may be that the cone of depression is reaching distant boundaries. This type of response is said to be fairly typical in Coal Measures boreholes and the fact that it does not seem to have been widely reported previously, is a reflection of the lack of published material. As Coal Measures yields have frequently been noted to decline with time, this 'creep' effect is likely to be far more common than is generally reported. Analysis of water levels which have not stabilised during the test period is likely to provide transmissivity values which are too high. In consequence, all values available for the Coal Measures should be viewed with some caution.

SPECIFIC CAPACITY

The higher specific capacities attributable to the Coal Measures Group to the west of the Pennines is almost certainly a reflection of the presence of thicker sandstone horizons. In the east Pennines there is a tendency for the higher specific capacity values to be located in the northern portion of the coalfield, again most probably a reflection of the greater number and thickness of sandstones in this area compared to further south. It is also possible that the values could be influenced by mining activities rather than sandstone thickness.

A plot of specific capacity and corresponding transmissivity data (available for only 11 sites) for the area to the east Pennines (Figure 8.32) shows no relationship between the two parameters for this limited data set. Given the multilayered nature and complex nature of the Westphalian aquifer horizons, this lack of correlation is not entirely unexpected.

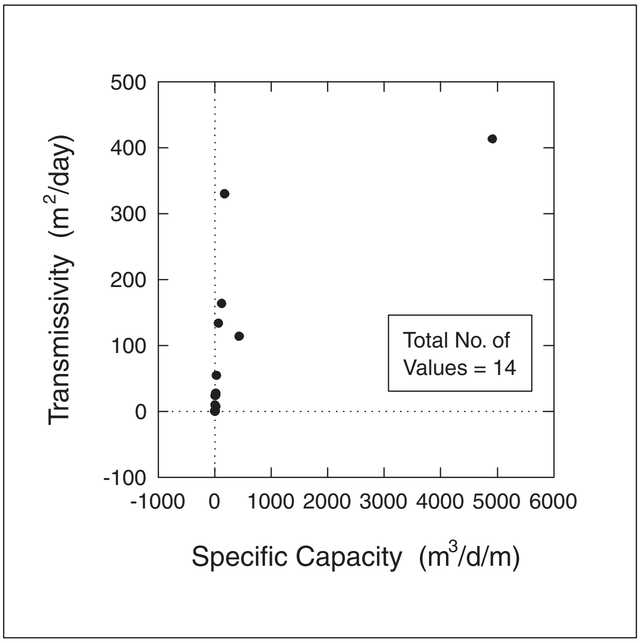


Figure 8.32 Correlation between specific capacity and transmissivity for the Coal Measures Group for the area to the east of the Pennines.

8.7 NORTHERN ENGLAND

8.7.1 Geology and stratigraphy

8.7.1.1 *Extent of aquifer group, stratigraphy and lithology*

The Carboniferous outcrop in northern England extends from the west coast between Whitehaven and Maryport in an arc around the northern and eastern flanks of the Lake District Massif. It rounds the southern end of the Vale of Eden and occupies virtually all of the area to the east, with the exception of the Cheviot Hills area on the Scottish borders (Figure 8.33).

To the west of the Vale of Eden, the Dinantian occupies a broad outcrop adjacent to the Lake District Massif but narrows distinctly to the south of Cockermouth. The Millstone Grit outcrop lies to the north but is, by comparison, narrow and often discontinuous due to faulting. The Coal Measures outcrop occupies a broad area in the west, extending along the coast from Whitehaven to Maryport before narrowing and becoming more discontinuous to the east and disappearing against the northern part of the Vale of Eden.

The Dinantian outcrop to the east of the Vale of Eden, narrows northward before broadening rapidly to the north-east, reaching the North Sea coast to the north-east of Alnwick and extending as far north as Berwick-upon-Tweed.

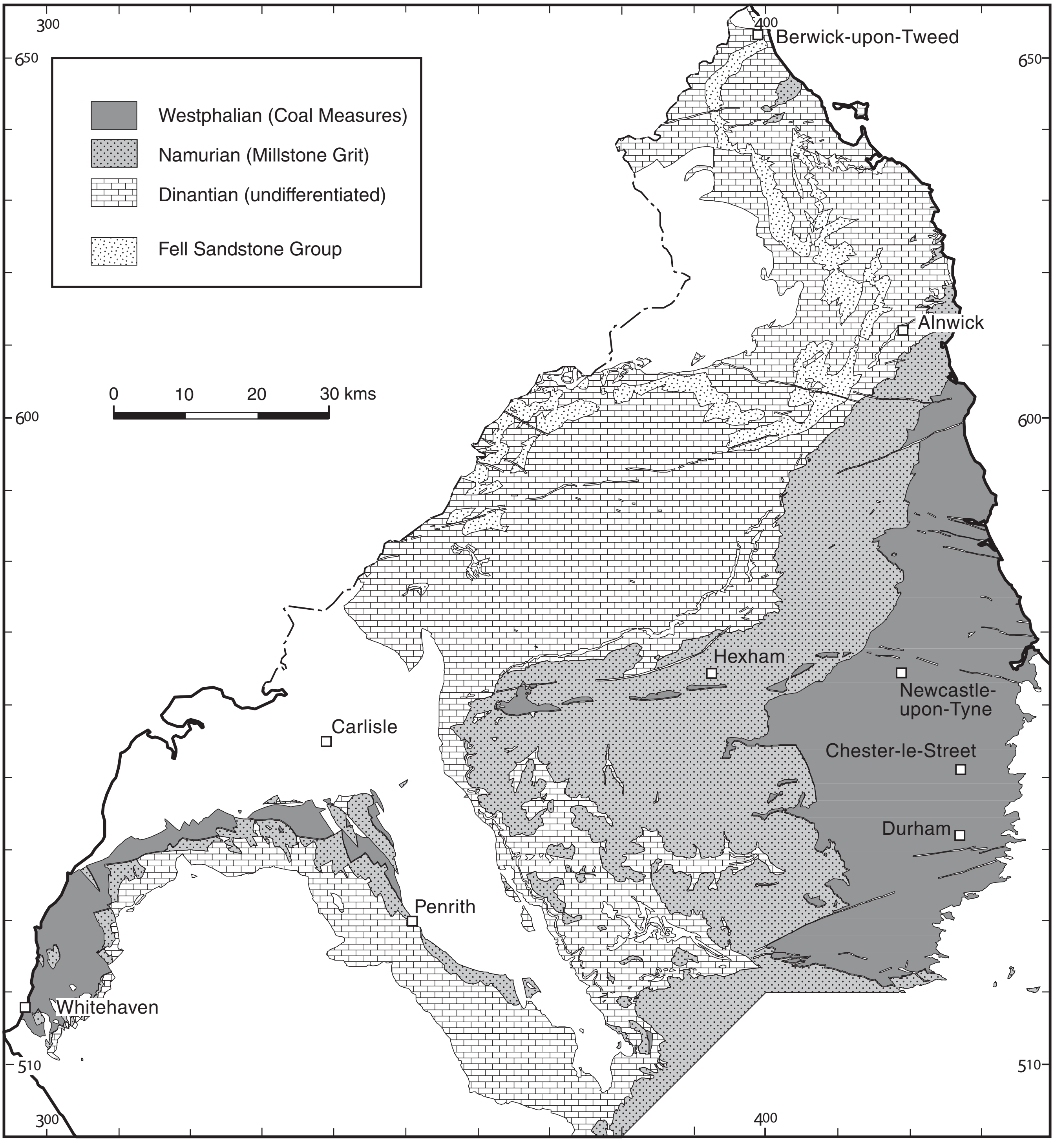


Figure 8.33 Distribution of Carboniferous outcrops in northern England.

The most important aquifer within the Carboniferous sequence of northern England is the Dinantian Fell Sandstone Group, a description of which will form a major part of this section. The outcrop of this group forms a thin curve, flanking the Cheviot Hills (Figure 8.34). Elevation varies from sea-level up to about 440 m; the sandstones form a craggy escarpment with dip slopes generally to the south-east. Agricultural development is limited by the thin acidic podzolic soils that have developed on the sandstone and so land cover is often heather moor (Hodgson and Gardiner, 1971). The northern outcrop is drained by tributaries of the River Tweed and in the south by the Rivers Aln, Coquet, Font and Tyne. Springs are found throughout the hills.

The Millstone Grit outcrop lies to the south and east of the Dinantian outcrop. It is deeply dissected to reveal the underlying limestones in the south-west.

The Northumberland and Durham Coalfield occupies a roughly triangular area, the apex of which is near the mouth of the River Coquet and the base extends from near Hartlepool on the coast to Egglestone in south-west Durham. In the south-east of the coalfield, the Coal Measures are concealed beneath Permo-Triassic strata.

Dinantian

In northern England, the uppermost Dinantian strata are the upper part of the Alston Group of the Stainmore Trough and Alston Block. These comprise the typical 'Yoredale facies' of cyclical beds with a typical upward succession of limestone, mudstone, siltstone, sandstone, seatearth, coal. The Dinantian strata in the Northumberland Trough typically comprise cyclical beds of mudstone with either sandstone or limestone beds predominant.

The Fell Sandstone Group is a mid-Dinantian sequence of sandstones and mudstones of Chadian to Holkerian age (Leeder, 1992). At exposure the Fell Sandstone is essentially a friable medium-grained sandstone, commonly cross-bedded (Hodgson and Gardiner, 1971). Borehole lithological descriptions from the Tweed Basin, however, suggest that up to 60% of the group may be made up of mudstone (Turner et al., 1993). The proportion of mudstone and cementation increases to the south-west, effectively reducing both the permeability and effective porosity of the group (Day, 1970).

The group varies in thickness from about 170 to 350 m; it is thickest in the central part of the Northumberland Basin around Rothbury and Simonside (Turner et al., 1993). Underlying the Fell Sandstone is the Cementstones Group. Although generally of low permeability, the sandstones of this group have groundwater potential in the Redesdale and Tweed valley areas (Johnson, 1995). Overlying the Fell Sandstone, is the Scremerston Coal Group, which is predominantly an aquitard except in west Northumberland where it includes some sandstone units (Johnson, 1995).

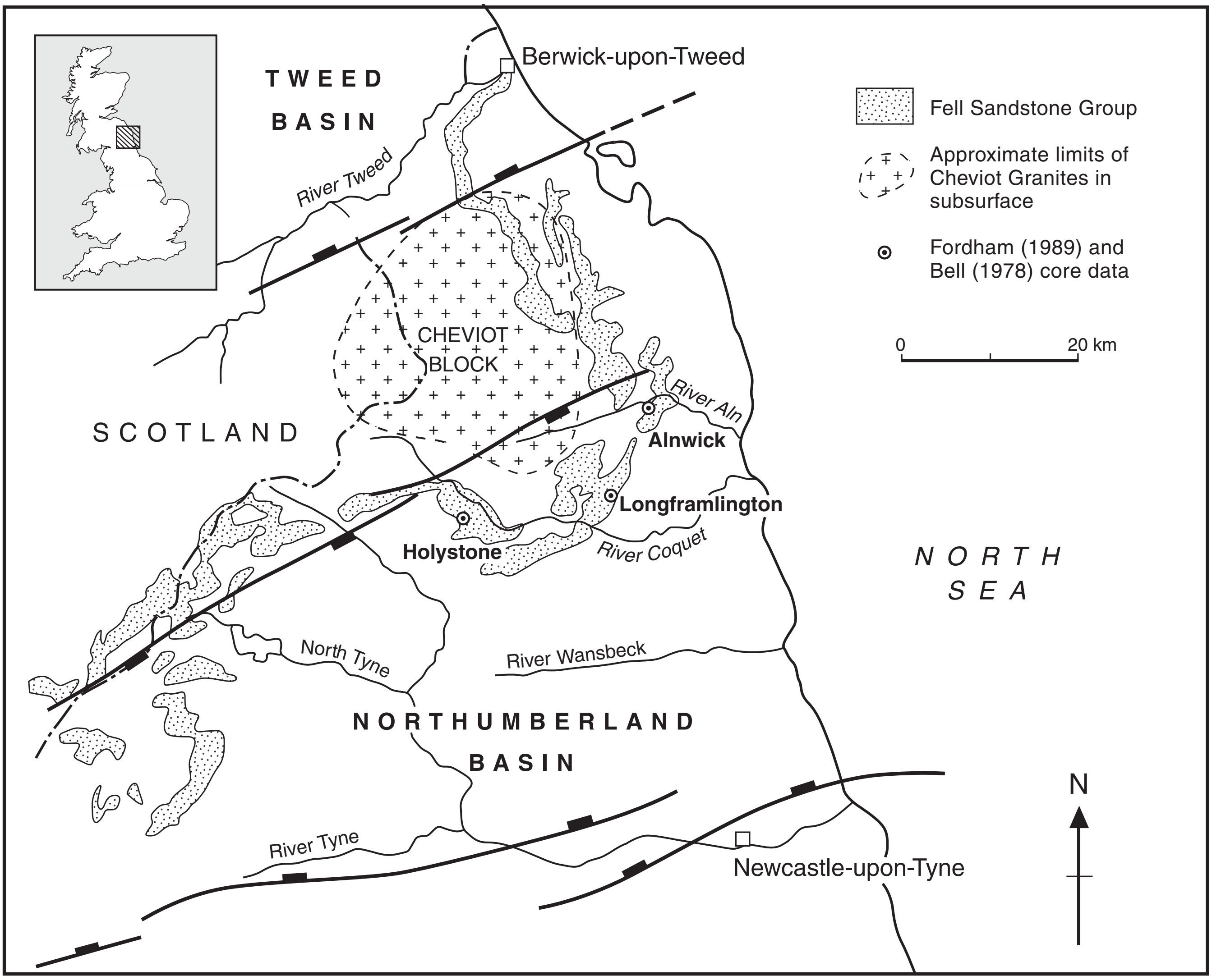


Figure 8.34 Distribution of Fell Sandstone Group outcrop in northern England (after Turner et al., 1993).

The Fell Sandstone Group was deposited by a major braided fluvial system which drained westward into a shallow, low energy sea. The sandstones are medium-grained, well-sorted quartz arenites. At outcrop they are usually red, while at depth they are generally light brown or white (Turner et al., 1993). Silica overgrowths and pyrite comprise the cement, with rare calcite (Bell, 1978a; Fordham, 1989). The sandstones are generally cross-bedded with some convoluted bedding and more massive horizons. Occasionally, thin conglomerates are observed with pebbles up to 25 mm (Hodgson and Gardiner, 1971). The mudstones, which are stiff, laminated and of various colours were believed by earlier authors to be thin and lenticular (Day, 1970; Hodgson and Gardiner, 1971), while more recent studies suggest they can be thick and laterally continuous (Turner et al., 1993).

Interest in the aquifer potential of the Fell Sandstone is concentrated around the town of Berwick-upon-Tweed. A recent lithostratigraphy study in this area was conducted to try to identify the various aquifer units within the Fell Sandstone Group (Turner et al., 1993). Seven mappable sandstone units were identified within the Tweed Basin varying from 10 to 70 m in thickness. These are separated by laterally continuous mudstones from 10 to 50 m thick. The distribution of the outcrop of the two lithologies is shown in Figure 8.35, and a simplified lithological stratigraphic column is shown in Figure 8.36 for the vicinity of Berwick-upon-Tweed. The two thickest sandstone units, the Peel Knowe Formation and the Murton Crags Formation, are the most important for water supply.

A simplified view of the structure is shown in Figure 8.34. The average dip is generally less than 10° to the south-east. Major faults trending east-north-east cut the outcrop. These faults are believed to have a dextral strike slip component and can have downthrows in excess of 200 m (Cradock-Hartopp and Holliday, 1984). Many other faults are present in the area, striking east-south-east as well as east-north-east. Pre-Permian dykes are associated with the east-north-easterly faults; Tertiary dykes are associated with the east-south-easterly faults.

Recent geomorphological studies (Younger and Stunnel, 1995) have identified various surface pseudo-karst phenomena associated with the Fell Sandstone Group: (1) rillenkarren (the terms 'clint' and 'grike' are often used in the UK) have been identified on many outcrops; (2) caves, arches and dolines have been found at several locations; and (3) honeycomb weathering, decantation flutes and 'pits and pans' have also been identified.

Namurian

In the south of the area, Namurian strata mainly consist of Millstone Grit facies typically comprised of coarsening-upward cycles ranging from dark grey carbonaceous shales, grey silty mudstones and siltstones, feldspathic fine- to very coarse-grained sandstones (the latter formerly referred to as grits), with subordinate coals and residual soil horizons typically capping the cycles in the upper part of the group. The sandstones are often upward- coarsening with gradational bases and sharp tops, representing progradation of delta-top

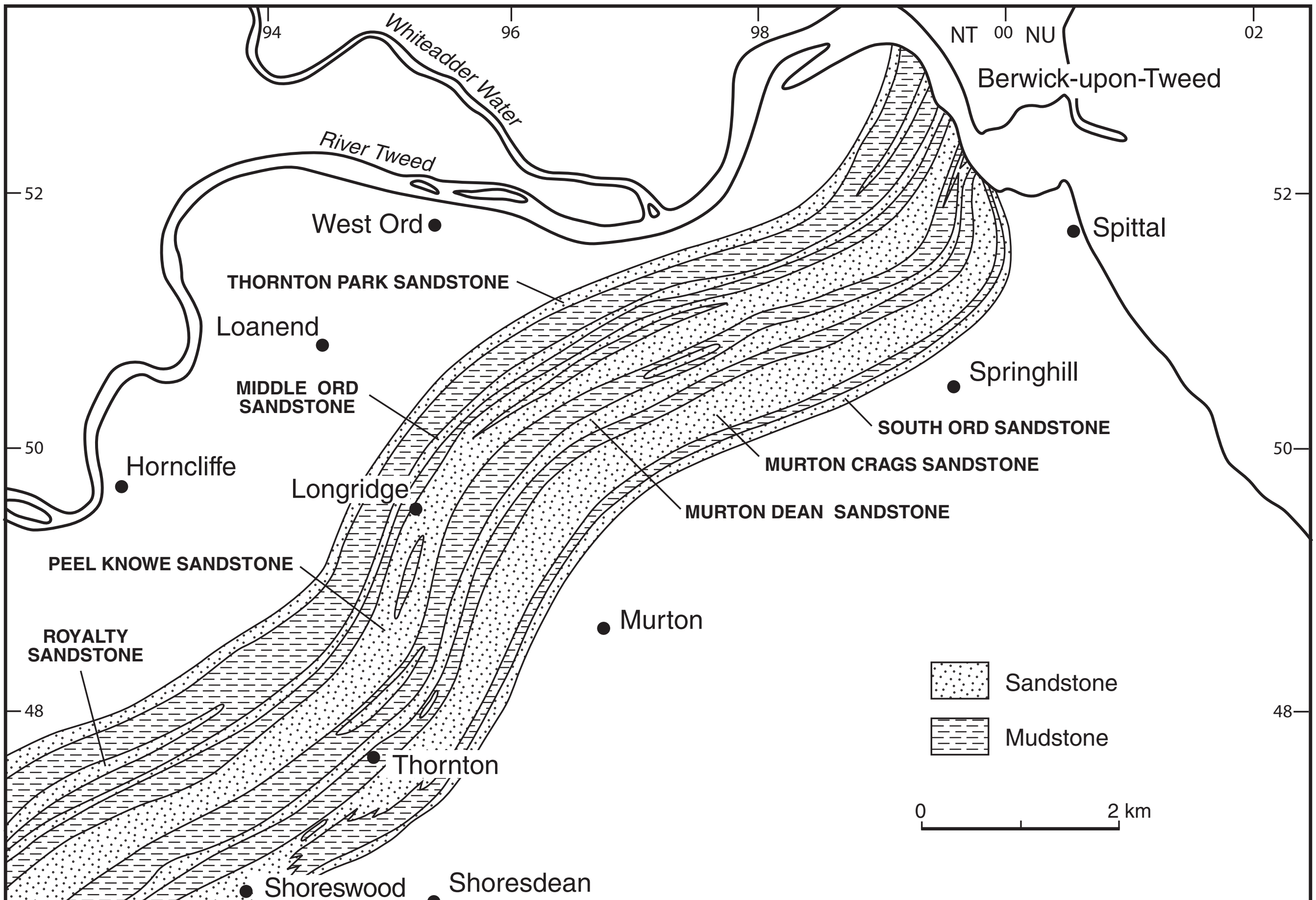


Figure 8.35 Lithostratigraphical map of the Fell Sandstone Group around Berwick-upon-Tweed (after Turner et al., 1993).

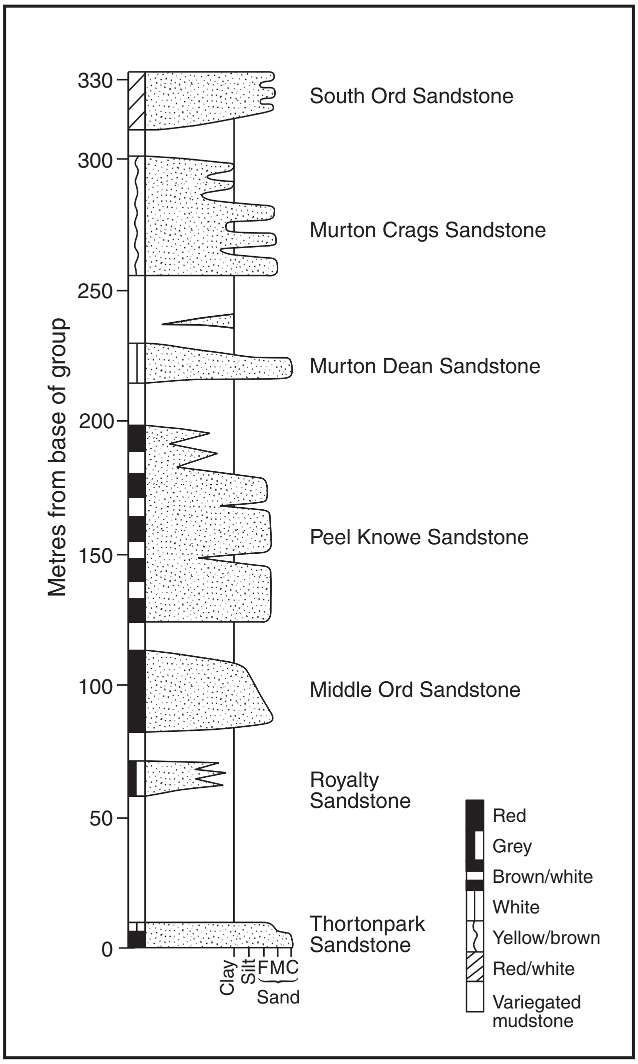


Figure 8.36 Generalised stratigraphical column for the Fell Sandstones Group in the vicinity of Berwick-upon-Tweed (after Turner et al., 1993).

sand-bodies. Sandstones can range from coarse-grained and cross-bedded or massive to fine-grained, micaceous and thinly planar laminated.

Further north, coarse pebbly sandstones only occur locally and are most common in the upper Marsdenian and Yeadonian parts of the sequence, comprising the First and Second Grits of Durham, southern Northumberland and the Brampton area. In north and west Northumberland and north Cumbria, the marine deposits become more calcareous and relatively thick limestones are common within a predominantly argillaceous sequence. In west Cumbria, the Hensingham Grits constitute a particularly thick and more coarse-grained horizon near the base of the sequence. The positions of the more significant grit and sandstone horizons in the Millstone Grits of the area and their correlation with horizons in the Pennines area are shown in Figure 8.5.

Westphalian

The Coal Measures Group successions in the Durham and Northumbrian coalfields are very similar, consisting of cyclic sequences of coal, shale and sandstone, in which argillaceous strata predominate. The Lower and Middle Coal Measures have a total thickness of about 725 m with most of the productive coals concentrated in the middle of these strata (Taylor et al., 1971). In the lower part of the Lower Coal Measures, sandstones tend to be coarse and some are siliceous. A thick horizon of gritstone, the ‘Third Grit’ of Durham, is also contained in this part of the succession. Massive sandstones occur in the upper part of the Middle Coal Measures. The Upper Coal Measures are only present in two small areas of the coalfield and consist of mudstones, siltstones with subordinate sandstones and a few thin coals.

In the Cumberland coalfield, strata are heavily faulted and dip radially away from the Lake District Massif. The succession is considerably condensed being, at its thickest, 450 m in the Workington area. Argillaceous strata again are predominant in the Lower and Middle Coal Measures with locally thick sandstones which thin laterally or pass into mudstones. The Upper Coal Measures are relatively poorly known in the area but, although the lower part appears to consist of normal grey shales and sandstones with residual soil horizons, the majority of the succession is of red and purple shales, mudstones and sandstones with occasional thin limestones.

8.7.2 Hydrogeology

8.7.2.1 *Introduction*

Dinantian

FELL SANDSTONE

The Fell Sandstone Group is the most important aquifer in Northumberland. For over a century it has been exploited for public supply for Berwick-upon-Tweed, where despite earlier problems with saline intrusion, boreholes continue to supply the town. Demand over the rest of the outcrop of the aquifer is low, although numerous farm boreholes tap the formation. Springs are common over the dales and are used for public supply at Rothbury. Intensive farming is not practiced in the area due to the poor farming land. Consequently the aquifer has been little affected by agricultural contamination.

The first hydrogeological study of the Fell Sandstone was carried out in the early 1970s (Hodgson and Gardiner, 1971). This estimated that the Fell Sandstone had significant groundwater resources which were then underutilised. Bell (1978a; b) analysed core samples from the Fell Sandstone and estimated both the physical and mechanical properties of the sandstone. Cradock-Hartopp and Holliday (1984) investigated the geothermal potential of the Fell Sandstone as part of a national study. More recently, a lithostratigraphy study of the Fell Sandstone was commissioned by the National Rivers Authority and carried out by the University of Newcastle upon Tyne (Younger, 1991; Turner et al., 1993; Younger and Stunnel, 1995). Several postgraduate theses have also been conducted on data from the Fell Sandstone (e.g. Fordham, 1989).

The Fell Sandstone aquifer is complex, being multilayered and separated by several thick mudstone units. Fractures have a significant impact on flow through the Fell Sandstone, and even within the sandstone units there are specific flow horizons. A brief discussion is given below on the main factors thought to be controlling the aquifer properties.

The first major hydrogeological study of the Fell Sandstone Group (Hodgson and Gardiner, 1971) suggested that the aquifer acted as a single unit; mudstone horizons were either too thin or lenticular to restrict groundwater movement. However, recent detailed studies of the group around Berwick-upon-Tweed (Younger, 1991; Turner et al., 1993) have established that the Fell Sandstone comprises up to seven discrete sandstone aquifers separated by thick, laterally persistent, mudstone layers acting as aquitards. Most significant for water supply are the two thickest sandstones, the Murton Crags Formation and the Peel Knowe Formation. Pumping tests in the Murton Crags Formation indicated negligible leakage through the mudstones from underlying or overlying sandstones (Turner et al., 1993). Little is known about the aquifer to the south and west, but mudstone layers are thought to become more significant (Hodgson and Gardiner, 1971).

The Fell Sandstone aquifer has relatively low matrix porosity and permeability. Bell (1978a; b) in studying aquifer parameters and sedimentology in a borehole at Longframlington could not find any significant relation between core aquifer properties and particle size, sorting or cement content. Grain packing was the only factor found to influence porosity and permeability. However, Fordham (1989) in his study of core data from three boreholes, including Longframlington disagreed, finding that grain size was the main influence on porosity and permeability; coarser grained sandstones had the highest porosity and permeability. Turner et al. (1993) suggest that the coarser-grained sandstones have higher preserved primary porosity and also a greater degree of secondary dissolution porosity due to a larger proportion of unstable minerals. Dissolution of pyrite and (rare) carbonate cements could also enhance porosity (Monro, 1986).

Fracture flow is significant in the Fell Sandstone aquifer. The mean matrix permeability obtained from analyses of the data collected for this project is in the order of 0.002 m/d which, integrated over a thickness of 100 m, would only give a transmissivity of 0.2 m^2/d. Transmissivity values measured from pumping tests, however, are commonly 100 m^2/d, therefore, the majority of flow must be from discrete horizons: either fracture flow or from thin coarse or sandy horizons. Vertical fractures with iron staining on the fracture surfaces have been noted both at outcrop and in core samples (Hodgson and Gardiner, 1971). Faulting is more common than implied in Figure 8.34, and larger faults may have significant downthrow, sometimes in excess of 200 m. However, throws are more commonly less than 60 m (Cradock-Hartopp and Holliday, 1984). Tertiary and pre-Permian dykes follow many of the faults, and may be associated with large springs e.g. near Rothbury two springs yield together in excess of 9000 m^3/d (Cartington Spring [NU 042 044], Tosson Spring [NU 030 002]).

Recent drilling has shown that much groundwater is associated with soft sandy horizons found at the base of the sandstone units (M Kershaw, personal communication). These sandy horizons can form running sand when drilling. Pumping can develop these layers significantly, thus improving yield (Figure 8.37).

OTHER DINANTIAN AQUIFERS

The nature of the remainder of the Dinantian aquifer horizons varies considerably across the area. The limestones and sandstones are water bearing whilst the interbedded shales and mudstones act as aquicludes or aquitards. The limestone matrix has a very low porosity and permeability, making a negligible contribution to total groundwater flow. The limestones only constitute an aquifer due to the presence of a secondary network of solution enlarged fractures and joints which often form complex branching systems. Groundwater flow is largely concentrated in the larger conduits and directed towards discrete points of discharge (single springs or groups of springs). Groundwater flow directions are often difficult to predict and may change markedly with variations in water table levels, as discrete solution-enhanced fracture networks are dewatered.

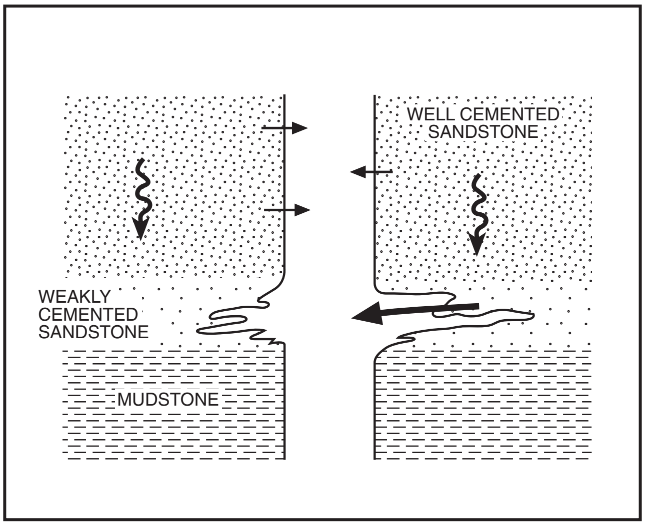


Figure 8.37 Schematic diagram showing flow from sandy layers.

Borehole yields from the limestones are highly variable, very productive if large conduits are intersected but low yielding or occasionally completely dry if no fractures are encountered. Their density and size commonly decrease rapidly with depth. The unpredictability of the aquifer combined with the fact that the Carboniferous Limestones underlie extensive tracts of sparsely populated uplands which are well supplied with surface waters, has militated against the drilling of boreholes to exploit groundwater resources. Borehole yields in northern England are, from the very limited information available, highly variable generally ranging from less than 9.6 m^3/d to almost 250 m^3/d. Occasionally higher yields are obtainable where the limestones are thicker and better fractured, for example a yield of almost 408 m^3/d was obtained from a borehole penetrating the Great Limestone beneath the Permian sandstones near Appleby (Ministry of Housing and Local Government, 1961 and 1966; Frost and Holliday, 1980). At Barrasford Sanitorium [NY 9225 7646] a 180 mm diameter borehole, which penetrated the Liddesdale Group to a depth of about 75 m, obtained an artesian flow which varied from 216 to almost 600 m^3/d from fractures in the Low Tipalt Limestone (Frost and Holliday, 1980). Very low yielding and dry boreholes, which would not have been tested, are however by no means likely to be uncommon. Yields for the seven sites in the area, contained in the Minor Aquifers Database, range from 96 to 984 m^3/d.

Boreholes in close proximity can often produce very different yields if water-bearing fractures are encountered in one borehole but not in others. At Garrigill [NY 745 415] three boreholes all penetrated the limestones between the Scar Limestone and Tyne Bottom Limestone, producing yields of 10, 29 and 16 m^3/d. However, in the first and third boreholes, drawdowns were 40 m and 30 m and still declining (as were the yields) at the end of the test, whilst at the second borehole the test achieved equilibrium at a drawdown of 8.5 m (Campbell, 1986).

In the area to the east of the Vale of Eden, the Carboniferous Limestone contains veins of lead and other minerals which have been mined in the past. As was the case in the Peak District (Allen et al., 1997), mine drainage adits (soughs) were driven underground from a low point in order to drain the workings. Langthwaite Level (locally known as Goose Nest) flowed at rates ranging from 20.4 to almost 144 m^3/d during the late 1960s and early 1970s (Yorkshire Water Authority correspondence October 1975) providing approximately 12 m^3/d to supply the villages of Langthwaite [NZ 005 025] and Arkle Town [NZ 008 019]. The mine drainage adit at Fewsteads [NY 7408 4258] was also used for public supply although this water was of poor quality due to excessive concentrations of heavy metals. In this area extensive mine workings will have caused a significant modification of the original hydrogeological nature of the limestones by creating interconnections between previously separated limestone and sandstone aquifer horizons as well as creating preferential flow paths now discharging at mine entrances and adits (North West Water, 1985).

Namurian

The Millstone Grit constitutes a multilayered aquifer in which the thick, massive grit, sandstone and limestone horizons effectively act as separate aquifers with the intervening mudstones and shales acting as aquicludes or aquitards. The Millstone Grit horizons most likely to constitute aquifers in northern England include the First and Second grits of Durham, southern Northumberland and the Brampton area. In many places springs issue from the base of water-bearing horizons and have provided the source for small-scale village supplies.

Groundwater storage and movement in the well cemented grits, sandstones and limestones is predominantly through joints and fractures with only minor contributions from the rock matrix. Borehole yields are dependent on the number and size of fractures encountered in a productive horizon. Many boreholes penetrate more than one productive horizon. The groundwater potential of the main water bearing horizons is very variable and some horizons may only be of local importance. The unpredictability of the aquifer combined with the fact that the Millstone Grit underlies extensive tracts of sparsely populated uplands which are well supplied with surface waters, has militated against the drilling of boreholes to exploit groundwater resources. Few boreholes have in fact been drilled to provide water supplies but yields of the order of 25 m^3/d have been recorded (Ministry of Housing and Local Government, 1961).

Westphalian

The Coal Measures Group form a complex multilayered minor aquifer. Argillaceous strata predominate, acting as aquitards or aquicludes, isolating the occasional thicker sandstone horizons which effectively act as separate aquifers. Coal Measures sandstones are very well cemented, extremely hard and dense and in consequence possess very little primary porosity or intergranular permeability. In the north-east, sandstones constitute up to 30% of the succession (Minett et al., 1986). Groundwater storage and movement occurs predominantly within and through fractures in the sandstones. The sandstones are generally fine grained and well cemented and often laterally impersistent. Mining-induced subsidence has created hydraulic continuity between the layers and in some locations with the mine workings. Sandstone permeability is directly related to the distribution and size of fractures present in the sandstone horizons. The Coal Measures are extensively folded and faulted, creating isolated blocks of aquifer which inhibit lateral water movement.

Borehole yields are dependent on penetrating a productive sandstone horizon and the number, size and lateral extent of fractures encountered. Very few water supply boreholes and wells are recorded as penetrating the Coal Measures Group in the north-east. Yields of up to a few m^3/d have been recorded (Ministry of Housing and Local Government, 1961) whilst in the Morpeth/Bedlington/Ashington area yields range from 72 to 1992 m^3/d, with most boreholes having some yield (Jackson and Lawrence 1990). Yields may decline with time as storage is depleted in sandstones which receive little or no direct recharge.

Mine workings in the Durham Coalfield were extensively interconnected and, when in operation, groundwater levels were maintained at depths of about 150 m below ground level by pumping (Downing, 1998). Abstraction from the collieries generally ranged from 624 to 6360 m^3/d but some pumped much more. In 1959 almost 115 200 m^3/d was pumped from the exposed section of the coalfield and 151 200 m^3/d from the concealed section, a total of over 266 400 m^3/d. In 1972 a total of 346 000 m^3/d was being pumped from 158 mines, (of which 56 were operational and 102 disused), in the Northumberland and Durham coalfield (Rae, 1978a). In the Cumberland Coalfield individual colliery discharges ranged from about 360 to 2400 m^3/d and totalled over 9120 m^3/d in the early 1960s (Ministry of Housing and Local Government, 1966). In the western part of the coalfield the entry of water to collieries was such that some were forced to close, leaving unworked coal reserves, when the cost of dewatering became prohibitive (Hopkins, 1951). Borehole yields may be enhanced where water-filled mine workings are penetrated although frequently water quality is poorer. In the Cumberland Coalfield saline waters were pumped from workings beneath the Solway Firth and could be drawn inland from interconnected workings some distance from the coast.

8.7.2.2 *Core data*

Dinantian

The only laboratory measurements of aquifer properties carried out on Dinantian rocks in the area are for samples obtained from the Fell Sandstone. The aquifer properties database contains core analyses for 112 samples, taken from eight locations. Some of the samples have been taken from greater than 400 m depth. The porosity data are shown in Figure 8.38; values range from 1.4% to 23%, but typically lie between 6% and 12% (Table 8.13). The distribution of hydraulic conductivity data are shown in Figure 8.39. Measurements typically lie between 2×10^{-5} and 5×10^{-2} m/d, with a geometric mean of 0.0016 m/d. Plotting porosity against hydraulic conductivity shows a strong linear relationship ($r^2 = 0.70$) (see Figure 8.40).

There are several published studies on permeability and porosity variations in the Fell Sandstone Group. Hodgson and Gardiner (1971) carried out laboratory determinations of porosity and permeability on 75 samples. Most were taken from surface outcrops selected on a random basis and they include both vertical and horizontal orientations. Samples from littoral environments are distinguished from those of other genesis. Mean porosity of the non-littoral samples is 12% and the littoral samples 18.6% (Table 8.13). The geometric mean of hydraulic conductivity for the non-littoral and littoral samples is 0.012 and 0.18 m/d respectively (Table 8.14). Cradock-Hartopp and Holliday (1984) state that the mean porosity and hydraulic conductivity of the borehole data within the Hodgson and Gardiner (1971) dataset are 8.8% and 0.005 m/d respectively, values which correspond with the data held on the Aquifer Properties Database (see below). Thus the results from outcrop are significantly higher than those from boreholes, implying that both porosity and hydraulic conductivity are enhanced

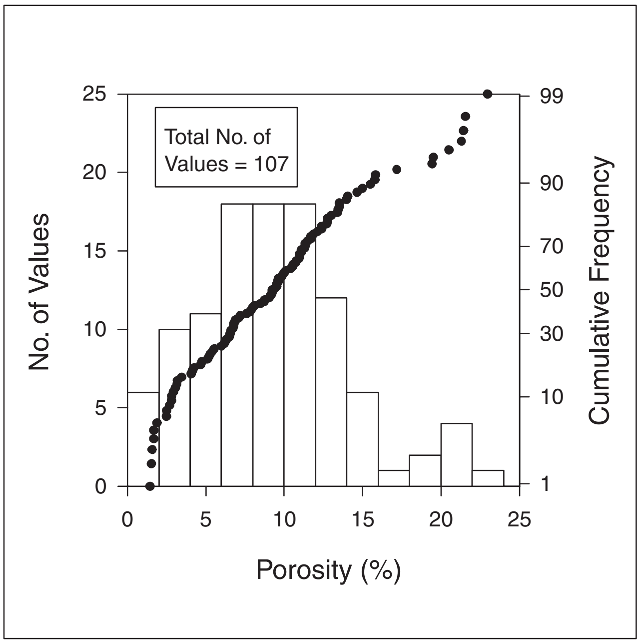


Figure 8.38 Distribution of porosity data for the Fell Sandstone Group of northern England.

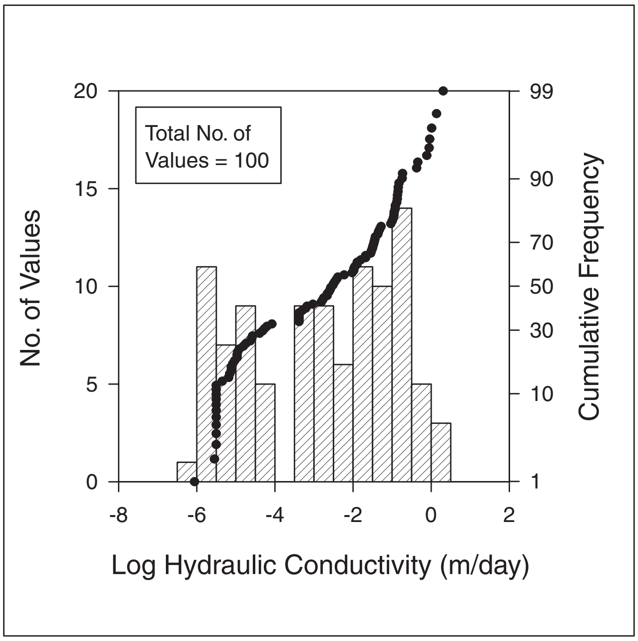


Figure 8.39 Distribution of hydraulic conductivity data for the Fell Sandstone Group of northern England.

at outcrop. This increase in porosity and permeability is attributed to the fact that weathering causes a loss of cement and renders the sandstone more friable than its equivalent at depth.

Bell (1978a; b) determined porosity and permeability for samples from 0 to 94.5 m in a borehole on Longframlington Common. Porosity was measured in a variety of ways; data quoted here are those using the resaturation method, the same as that used in the BGS aquifer properties laboratory, from which all BGS core analyses are derived. The variation of porosity and hydraulic conductivity with depth is shown in Figure 8.41. Porosity declines from approximately 12% at outcrop to 7% at 90 m; hydraulic conductivity shows little variation with depth varying between 0.11 to 0.15 m/d. A coarse horizon at 24.4 m has a significant impact on the matrix properties. The porosity of this horizon, 20%, is much higher than that measured in the rest of the borehole, with a corresponding hydraulic conductivity of 0.43 m/d.

Fordham (1989) analysed core from three boreholes, Holystone, Alnwick and, Longframlington. The Longframlington Borehole was the same core studied by Bell (1978a; b). Over 100 samples were tested using thin sections and a mini-permeameter. A direct relationship was proved between porosity and permeability for the boreholes (Turner et al.,

Table 8.13 Summary of matrix porosity and hydraulic conductivity data for core samples from the Fell Sandstone Group.

Dataset	**BGS Database**	**Hodgson and Gardiner (1971)**		**Bell (1978)**
		All samples excluding littoral	Littoral borehole	Longframlington
Porosity (%)				
No. values	107	55	20	25
Minimum	1.4	1.0	5.7	6.5
Maximum	23	24.3	33	20.5
Arithmetic mean	9.3	12.0	18.6	9.6
Median	9.2	12.7	19.4	9.5
Interquartile range	5.9	6.6	8.7	2.5
Permeability (m/d)				
No. values	100	52	20	16
Minimum	8.8×10^{-7}	0.00005	0.00073	0.09
Maximum	2.03	5.6	2.1	0.43
Geometric mean	0.0016	0.012	0.18	0.14
Median	0.0029	0.010	0.39	0.13
Interquartile range	0.047	0.057	0.43	0.04

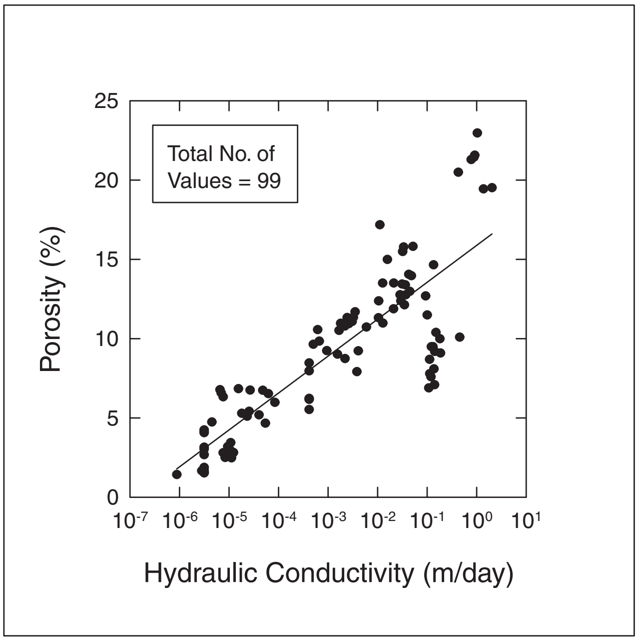


Figure 8.40 Correlation between permeability and porosity for the Fell Sandstone Group of northern England.

1993.), confirming the results obtained from analysis of the Aquifer Properties Database.

Namurian and Westphalian

No laboratory measurements of porosity or permeability of samples from Namurian or Westphalian strata are available.

Minett et al. (1986) reported that packer testing had obtained permeability values of 8.6 × 10^{-2} to 8.6 × 10^{-3} m/d for mudstones, sandstones and coal seams in Northumberland.

8.7.2.3 *Pumping test results*

Dinantian

Insufficient information is available to discuss in detail the areal distribution of aquifer properties in the Fell Sandstone. Data are concentrated around Berwick-upon-Tweed where the demand for water is highest. The southern extension of the two most productive sandstone units, the Peel Knowe Formation and Murton Crags Formation, is as yet unknown although Johnson (1995) suggests that the Fowberry borehole [NU 027 293] and Rothbury springs take water from the Murton Crags Formation.

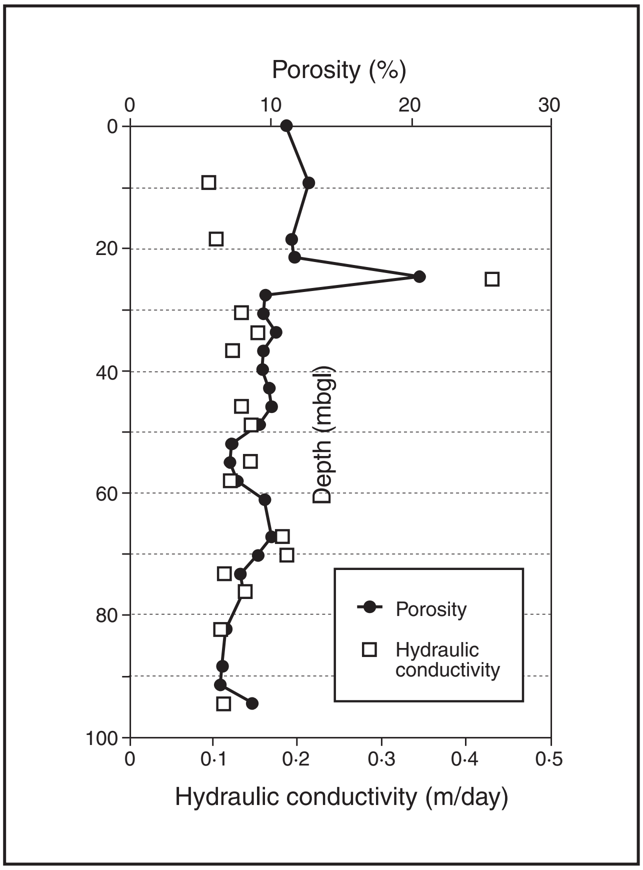


Figure 8.41 Fell Sandstone Group : change of permeability/porosity with depth (data from Bell, 1978a; b).

Data for the remainder of the Dinantian sequence is very sparse. Four sites are located on the outcrop to the east of the Vale of Eden but three of these are trial boreholes positioned close together near Garrigill [NY 745 415]. A further four sites are spaced evenly along the outcrop to the south-west of the Vale of Eden.

Aquifer properties data

Pumping test data results were available for 25 sites in the Fell Sandstone aquifer. Twenty eight pumping tests have been carried out giving 28 estimates of transmissivity, but only one storage coefficient. Transmissivity results are plotted in Figure 8.42. The data approximate to a log-normal distribution with a geometric mean of 81 m^2/d and a median value of 98 m^2/d. Although values range from 9 to

Table 8.14 Transmissivity and specific capacity data from pumping tests for the Fell Sandstone aquifer.

Fell Sandstone records		
Number of transmissivity values	28	—
Minimum/maximum transmissivity value (m^2/d)	9	692
Arithmetic/geometric mean of transmissivity (m^2/d)	119	81
Median/interquartile range of transmissivity (m^2/d)	98	108
25/75 percentile of transmissivity (m^2/d)	49	157
Number of specific capacity records	17	—
Minimum/maximum specific capacity values (m^3/d/m)	15	525
Arithmetic/geometric mean of specific capacity (m^3/d/m)	159	102
Median/interquartile range specific capacity (m^3/d/m)	83	200
25/75 percentile of specific capacity (m^3/d/m)	53	253

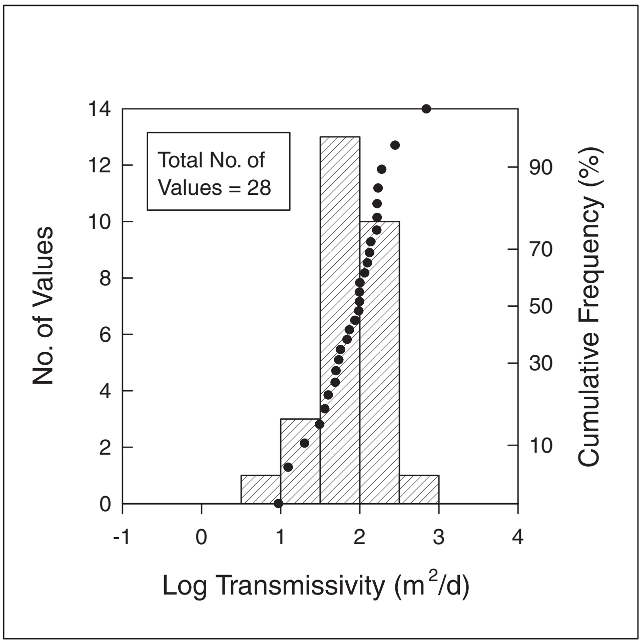


Figure 8.42 Distribution of transmissivity data from pumping tests in the Fell Sandstone Group of northern England.

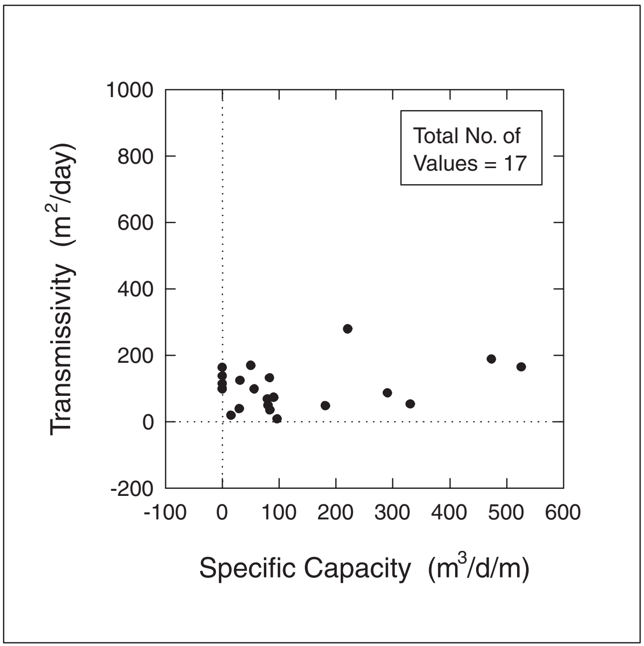


Figure 8.43 Correlation between specific capacity and transmissivity for the Fell Sandstone Group of northern England.

690 m^2/d the interquartile range is fairly small, with a 25 percentile of 49 m^2/d and a 75 percentile of 157 m^2/d. Specific capacity data are available for 17 sites in the Fell Sandstone. These data are not correlated with the measured transmissivity values (Figure 8.43).

The single estimate of storage coefficient calculated from a pumping test is 4×10^{-4} measured from Thornton Bog. However, an estimate of the specific yield has been made from thin sections for several core samples in the Fell Sandstone (Younger, 1992). Three different cores were tested, having a specific yield of about 0.1. Patently, more data are required on the storage characteristics of the Fell Sandstone, but from the few values currently available, approximations of 10^{-4} for confined and 0.1 for unconfined could be used for the storage coefficient.

When considering the remainder of the Dinantian sequence, it would be logical to suggest that yields and specific capacity would be lower in areas underlain by Yoredale facies, where mudstones and shales are dominant, and higher in areas where limestones are dominant. The available data are too sparse to show any such correlation.

TRANSMISSIVITY AND STORAGE COEFFICIENT

Transmissivities are only available for the three trial boreholes located near Garrigill. Of the three only that for borehole 2 (82.5 m^2/d), which attained equilibrium, is considered valid. The other two values (3 and 16 m^2/d), may be overestimates of transmissivity. No storage coefficients are available.

SPECIFIC CAPACITY

Specific capacities are available for eight sites in the Vale of Eden, with values ranging from 2 to 33 m^3/d/m in the south-west and 6 to 82 m^3/d/m in the north-east. As stated above, only one of the three trial boreholes located near Garrigill attained equilibrium during the test period. Boreholes 1 and 3 gave specific capacity values of 6 and 13 m^3/d/m respectively but, since equilibrium was not attained during either test, the true specific capacity values should be lower. Borehole 2 did attain equilibrium and gave a value of 82 m^3/d/m.

Namurian

The only pumping test data for Namurian strata in northern England, are for four sites located in the vicinity of Armathwaite in Cumbria. These recorded only specific capacities, which were highly variable, ranging from 10 to 289 m^3/d/m.

Westphalian

No aquifer test data are available on the Minor Aquifers Database for Westphalian strata in northern England.

Reeves and Hammond (1979) provided a transmissivity value of 15 000 m^2/d and stated that the coefficient of storage indicated confined conditions. These values were calculated from recovery data obtained when pumping ceased in an old shaft which penetrated the Lower Coal Measures at an undefined site in Northumbria. Although not stated, it is probable that the shaft was connected to flooded disused workings at depth, which would categorise the abnormally high transmissivity value as an artifact of anthropogenic activity.

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9 Devonian minor aquifers

9.1 INTRODUCTION

9.1.1 General geology and stratigraphy

The Devonian minor aquifers of England and Wales which are described in this chapter refer to two distinct regions; Wales and the Welsh Borders, and south-west England. This treatment is dictated by the very different lithologies which are present to the north and south of the Bristol Channel. The former can be considered together as part of the Old Red Sandstone aquifer group. The latter lithologies are more diverse, with a much more detailed stratigraphic nomenclature.

The Devonian rocks of the two regions described above outcrop mainly in Devon, Cornwall, Somerset, Avon, south and central Wales, the Welsh Borderland and the West Midlands (Figure 9.1). Devonian strata lie concealed at depth below younger rocks in south-west and south-east England. The strata fall into three broad depositional environments:

- the continental red bed Old Red Sandstone
- marine, nearshore, clastic facies
- marine, offshore, deep water facies.

The Old Red Sandstone crops out in south Wales, the Welsh Borders and West Midlands while the two marine facies occur in Devon, Cornwall and Somerset (Bennison and Wright, 1969). In the subsurface of central and south-east England, rocks of both marine and continental facies have been encountered in boreholes, although Old Red Sandstone facies predominate.

The stratigraphic relationships of Devonian rocks in both regions are very complex, and have undergone reassessment in the last 40 years, following on longstanding difficulties in bed correlation across both regions. These reassessments have tended to generate multiple successions and an extensive formation nomenclature which has itself been subject to extensive changes. Slightly more successional detail is therefore provided in sections 9.2.1.2 and 9.3.1.2 on facies variations than is absolutely necessary, in order to provide a concise up to date review of current formation nomenclature. For the same reasons, the text contains slightly more detailed nomenclature than is possible to illustrate in the correlation figures.

9.1.2 General hydrogeology

The Old Red Sandstone of Wales and the Welsh Borders attains great thicknesses, but has limited permeability. This is due in part to the variety of lithologies, with low permeability mudstones, marls, and siltstones interbedded with the sandstones. Thick calcrete deposits may, in contrast, provide zones of higher permeability. Primary porosity is usually low, and the predominant groundwater flow mechanism is via fractures.

The Devonian strata of south-west England also possess low primary porosity. Depositional and post-depositional effects have reduced the differences in flow and storage characteristics between the different lithologies, and it has been commented that structure, rather than lithology, dictates yields (Ussher, 1933). The effects of tectonism are variable across the area, but are generally much more intense than those that affected the Old Red Sandstone north of the Bristol Channel.

9.1.3 Aquifer properties data availability

Data were available from 200 pumping tests in the Old Red Sandstone of Wales and the Welsh Borders, and from approximately 160 tests for the Devonian of south-west England. The data for south-west England were subdivided on a lithological basis into three groups: arenaceous, carbonate, or argillaceous. Analysis was carried out on the full dataset, and also on the subsets, in order to evaluate whether the lithology influenced aquifer properties.

General groundwater flow data were also obtained from BGS memoirs (BGS, 1986) and other published sources.

Although there are other Devonian rocks present at depth, and less commonly elsewhere at outcrop, in England and Wales, no aquifer physical properties data for these quite limited occurrences were identified. They are considered unlikely to serve as minor aquifers of any significance. No core data were available.

9.1.4 General aquifer properties

Transmissivities for the Old Red Sandstone were very variable, ranging from 0.000001 to 350 m^2/d, with a geometric mean of 10.7 m^2/d. Specific capacities spanned a similar range. There were only three storage coefficient values, but these indicated semi-confined to unconfined conditions.

The Devonian strata of south-west England showed a similar range of transmissivity values, with a geometric mean of 4 m^2/d for all lithological types. The highest values were observed in the carbonate rocks. Storage coefficient values exhibited a very wide range, suggesting a wide variety of confinement conditions.

9.2 WALES AND THE WELSH BORDERS

9.2.1 Geology and stratigraphy

9.2.1.1 *Extent of aquifer group and stratigraphic relationships*

The outcrop of the Old Red Sandstone in Wales, the Welsh Borders and the West Midlands is approximately trapezoidal in shape, as shown in Figure 9.1. A sinuous westerly extension around the basin of the South Wales Coalfield reaches as far as Nab Head on the Dyfed coast while the eastern limit comprises the graben faults which mark the Worcester Basin (including the East Malvern Fault) and the Severn valley south of Bridgnorth.

Virtually everywhere, the base of the Old Red Sandstone rests on an erosion surface or angular unconformity. In most of south Wales and the Welsh Borderland, the Silurian — Devonian boundary actually lies within Old Red Sandstone facies, with the transition from marine to fresh

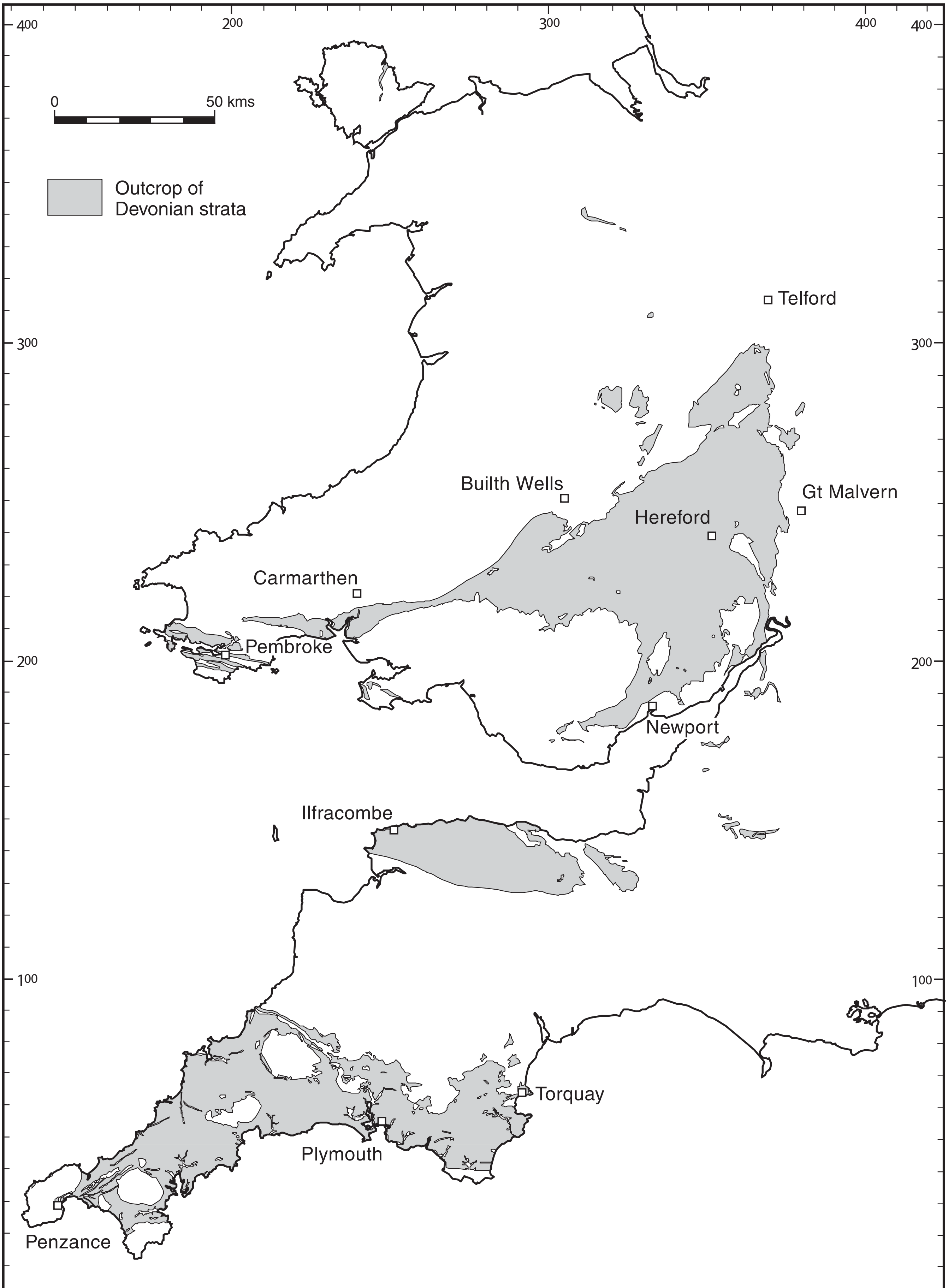

Figure 9.1 Outcrop of the Devonian rocks of Wales, the Welsh Borders and south-west England.

water deposition occurring in the late Silurian. This contrasts with south-west Wales, where Devonian strata rest with sharp unconformity on rocks ranging in age from Precambrian to Wenlock, and with Anglesey where they rest unconformably on Precambrian to Llandovery strata. Dinantian strata (the Carboniferous Limestone) succeed the Devonian rocks conformably in south Wales. In the Clee Hills of Shropshire, Namurian sandstones overlie unconformably the Old Red Sandstone. In south-east England, the rocks below the Devonian are unknown, but they are unconformably overlain by strata ranging from Coal Measures (Westphalian) to the Cretaceous Gault.

Figure 9.2 provides a schematic correlation of strata from the West Midlands to Anglesey which encompasses all of the regions main Old Red Sandstone outcrops. Total thicknesses are not known in detail in the east, but in south Wales the Old Red Sandstone is up to about 2500 m thick, with perhaps up to 5000 m of beds in south-west Wales. The correlation contains all of the most important formations referred to in the following section.

9.2.1.2 *Lithology and stratigraphy*

The Old Red Sandstone facies comprise coastal plain, alluvial plain and fluvial deposits in a generally upward-coarsening succession. Marine influence occurred sporadically in the Lower and Upper Devonian. The base of the Lower Old Red Sandstone succession spans the Silurian/Devonian boundary. It is marked by a phosphatic fossiliferous lag deposit, the Ludlow Bone Bed, at the base of the shallow marine Downton Castle Sandstone Formation (or Tilestones Formation of Powys). This is overlain in mid Wales and the West Midlands by grey to olive green siltstones (the Temeside Shales) of possible estuarine mudflat origin. All the above are ascribed to the Přídolí Series of the Silurian. Above them are the red mudstone- and siltstone-dominated successions above the Silurian–Devonian boundary. In Pembrokeshire/Dyfed these comprise the Sandy Haven Formation and the Moors Cliff Formation north and south of the Ritec Fault respectively. In south-east Wales and the Welsh Borderland they are termed the Raglan Mudstone (or Ledbury) Formation and in Powys the Gwynfa Formation (Almond et al., 1993). The strata consist of red mudstones and siltstones with sporadic fluvial sandstones and abundant calcretes. The last are mainly immature, nodular horizons, but massive, mature, stacked calcretes (the Psammosteus Limestone) lie at the top of the succession. Air fall tuffs lie near the top of the equivalent formation in Pembrokeshire/Dyfed, one of which (the Pickard Bay Tuff) extends to the Brecon Beacons area (Almond et al., 1993) and another (the Townsend Tuff) extends to Shropshire (Allen and Williams, 1981).

Shallow marine and coastal plain environments in the late Silurian/early Devonian were succeeded by increasingly terrestrial alluvial facies in the Lower Devonian as Dittonian strata conformably overlie the (Silurian) Přídolí Series. The St Maughans Formation of south-east Wales and the Welsh Borderland, the Gelliswick Bay Formation and Freshwater West Formation of Pembrokeshire/Dyfed and the Llanddeusant Formation of Powys comprise cyclic successions of fluvial, channel sandstones and overbank floodplain mudstones and siltstones. Calcrete occurs mainly as reworked clasts in common channel-base intraformational conglomerates, where fish fragments also occur. A thick conglomerate (Llanishen Conglomerate) at the top of the formation in south-east Wales was probably derived from the south.

The succeeding Breconian strata are of sandstone-dominated fluvial sandstone facies. Green sandstones in south Wales and the Black Mountains (Senni Beds) and Pembrokeshire/Dyfed (Cosheston Group) contain vascular plant remains. The Brownstones are mainly red fluvial channelised sandstones, with red-brown mudstone floodplain facies interbeds. They are the youngest Lower Devonian strata preserved, being unconformably overlain by Upper Devonian strata. Outliers of similar facies occur in the Dudley–Clee Hills area (Clee Formation). In Pembrokeshire/Dyfed, the Ridgeway Conglomerate consists of conglomerates, sandstones and siltstones with some calcretes. Sediment is thought to have been provided from the south and may be Middle Devonian in age, although a regional unconformity separates the Lower Devonian (Lower Old Red Sandstone) from the Upper Devonian (Upper Old Red Sandstone), as indicated in the correlation chart in Figure 9.2.

The Upper Old Red Sandstone (Farlovian) is represented by the Plateau Beds in the Brecon Beacons, Black Mountains and in the western part of the north crop of the South Wales Coalfield. These comprise a broadly transgressive sequence from fluvial and aeolian deposition to marginal marine environments. A basal granule-rich mudstone may be a mudflow. It is succeeded by fluvial, braided stream conglomerates, above which are cross-bedded red sandstones of possible aeolian origin, with some intercalated fluvial sandstones. The upper part of the succession comprises fish-bearing conglomerates and pebbly sandstones with interbedded red mudstones. These are overlain by a heterogeneous sequence of interbedded fine-grained, red-brown sandstones and mudstones. The Plateau Beds are overstepped by the Grey Grits, a sequence of fluvial (braided stream), grey, greenish and yellow quartzitic sandstones. These form the basal unit of the Quartz Conglomerate Group (the Wern Watkin Formation) in the north-east crop of the coalfield (Barclay, 1989). They are overlain by quartz pebble conglomerates (the Craig-y-cwm Formation), and in turn by micaceous, feldspathic and garnet-rich sandstones and interbedded red mudstones (the Garn-gofen Formation).

Conglomerates dominate the group on the south-east and south crops, in the Forest of Dean and Ross-on-Wye areas. The Garn-gofen Formation is the correlative of the Tintern Sandstone of the Forest of Dean. In Pembrokeshire/Dyfed, Upper Old Red Sandstone marine sandstones (the Skrinkle Sandstones) are early Carboniferous in age. In the Cardiff area, the Cwrt-yr-ala Formation underlies the Quartz Conglomerate Group. It comprises a succession of fining-upwards cycles of thinly interbedded fluvial sandstones and siltstones capped by mudstones with nodular calcrete (Waters and Lawrence, 1987). Upper Devonian yellow and white sandstones (the Farlow Sandstone) occur as an outlier on Titterstone Clee in the West Midlands.

9.2.1.3 *Structural and depositional history*

For the Lower Old Red Sandstone the effects of structures on deposition are best demonstrated in south-west Wales, where different successions lie to the north and south of the Ritec Fault. The striking differences between the sequences to the north and south of the fault indicate different depositional regimes existed. Pre-Carboniferous erosion of the Old Red Sandstone to the north of the fault suggests uplift continued on that side, while deposition continued to the south (Dineley, 1992). Devonian movement on the principal north-east-trending faults of Wales and the Welsh Border-

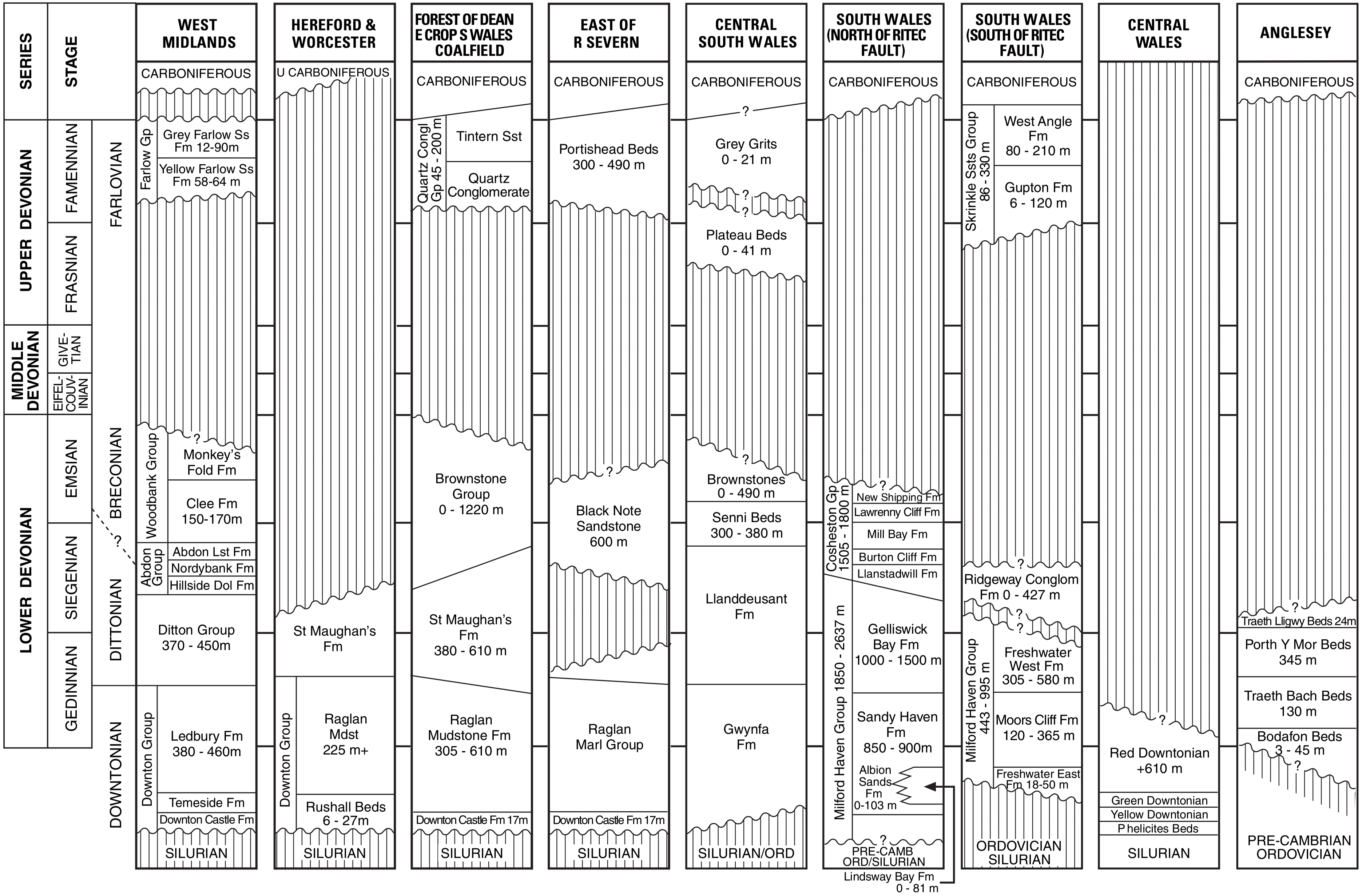

Figure 9.2 Correlation of Old Red Sandstone stratigraphy in Wales and the Welsh Borders (modified from House et al., 1977).

land is also likely. Tunbridge (1980), for example, has suggested that conglomerates near the top of the Brownstones in the Swansea valley area were probably deposited as a result of uplift of the Swansea Valley Fault. The intense, typically north-east-trending Caledonian deformation of pre-Devonian strata that is observed further to the northwest in Wales, is much subdued towards the Welsh Borders. The dramatic decrease in the intensity of folding and cleavage towards the south-east is such that Silurian and Lower Devonian strata lack a slaty cleavage and are only very gently folded parallel with the north-east-trending major basement lineaments such as the Pontesford-Linley and Church Stretton fault systems.

In the Lower Devonian, the occurrence of the Psammosteus Limestone (a widespread calcrete) suggests a period of regional uplift and non-deposition. The conspicuous absence of Middle Devonian strata from Wales and the Welsh Borderland is due to a regional unconformity caused by uplift and erosion during the Acadian episode of the Caledonian orogeny. Much of the Old Red Sandstone has low dips to the south or south-east, but internal unconformities occur between the lower and upper divisions in Shropshire and Gwent. Folding of late Caledonian and Hercynian origin occurs in the West Midlands and the Forest of Dean (Richards, 1957).

Heavy mineral suites and clay mineralogy (Parker et al., 1983) indicate shallow post-depositional burial depths for the Old Red Sandstone. The presence of epidote suggests burial of less than 1 km (Barclay et al., 1997).

Cementation and porosity are widely variable in the sandstones of the facies, some being weakly cemented and friable as a result of leaching of carbonate cement. Other sandstones are indurated with minimal primary porosity as a result of quartz overgrowth on the constituent grains.

9.2.1.4 *Jointing*

Published information on jointing patterns is limited to a single study by Roberts (1966) of jointing patterns along the northern flanks of the South Wales Coalfield. Joint sets in the Brownstones Group (shales and sandstones of the Lower Old Red Sandstone) were found at 350°, 330°, 270°, 240° and 220° (joint strikes being given as the larger of the two azimuths e.g. 350°–170° is recorded as 350° joint). The joints were best developed in the sandstone layers where characteristic joint sets with small dihedral angles predominated (350°–330°). They were reported to be smooth faced, planar, usually closed and persistent, with horizontal (strike) distances in excess of 15 m being common. Succeeding members of the Upper Old Red Sandstone were jointed along the same trends but the coarser lithologies gave rise to rougher, less rigidly parallel fractures. The topmost strata (Grey Grits) had a joint system with the master set striking at 340Þ and subordinate sets at 290°, 250° and 220°. These were reported as smooth-faced, planar, with an average frequency of 15 cm and a horizontal and vertical persistence of 15–18 m respectively. Roberts considered the majority of the joints to be shear fractures formed early in the deformational history of the area during the Hercynian orogeny.

9.2.1.5 *Igneous activity*

No Devonian intrusions into the Old Red Sandstone are known. In south Wales and the Welsh Borders, there are several ash fall tuffs of Early Devonian age, of which, the Townsend Tuff Bed is the most extensive. These form very valuable marker beds from south Wales to the West Midlands. They afford the only indication of Siluro-Devonian volcanic activity between Devon and the Cheviot area on the borders of Scotland (Dineley, 1992).

9.2.2 Hydrogeology

9.2.2.1 *Introduction*

In spite of the great thicknesses attained by the Old Red Sandstone, the permeability of this group is limited. In part this is due to the variety of lithologies encountered. Notwithstanding its name, the Old Red Sandstone as a whole is by no means dominated by sandstones. The continental terrestrial facies identified by researchers range from estuarine mudflats through fluvial floodplains to piedmont fans. Siltstones, mudstones and marls are all prominently interbedded and these fine-grained rocks provide a lithological barrier to horizontal and vertical water movement.

Marls and siltstones predominate in the lowermost Devonian strata (formerly known regionally as Downtonian) although entries in Table 9.1 indicate that subordinate sandstones like the Downton Castle and Holdgate sandstones can transmit water. Arenaceous beds are reported to predominate in the overlying beds (formerly known as Dittonian) but as well and spring yields appear to be typically only about two or three times higher than the underlying Downtonian (Richards, 1957) the frequent marl and siltstone bands must continue to exert control over water movement. In fact, it is reported that more than half the Lower Old Red Sandstone is represented by the predominantly argillaceous and essentially impermeable Red Marls or their equivalents (Holliday, 1986).

In contrast, thick calcrete deposits formed post-depositionally during periods of uplift and non-deposition provide zones of higher permeability. The nodular cornstones are more accurately described as calcreted mudstones, the calcrete or fossil soil horizons having formed in a semi-arid environment. The calcrete content of the matrix in these horizons increases to over 10%, but the nodules are associated with, and commonly built around, numerous branching, sub-vertical tubes filled with silt or sparry carbonate. These may originally have been animal burrows or root channels (Brandon, 1989). The effect on present day groundwater flow is not immediately obvious. However, the net effect appears to be to decrease permeability. This is illustrated by the fact that the most mature of the calcretes, the productive Psammosteus Limestone, is often marked in the field by marshy ground or springs as it separates the usually permeable Dittonian from the underlying poorly permeable marls of the Raglan Marl Group (Richards, 1957).

To these primary lithological controls are added the effects of poor sorting, frequent presence of micaceous material and induration arising from post-diagenetic compaction and burial. Primary porosity in some horizons of the Old Red Sandstone for instance is so low that they have long been used as resistant flagstones for building purposes. Associated cementation, both calcareous and siliceous, further decreases primary porosity, although this appears to be less the case in the Upper Old Red Sandstone, where the Quartz Conglomerate Group passes up into soft, poorly cemented fine- to coarse-grained sandstones (Holliday, 1986). In general however, the predominant Old Red Sandstone flow mechanism is via fractures, with much of the storage likely to occur in joint- and fault-related fracture systems.

9.2.2.2 *Previous studies*

The literature on the hydrogeology of the Old Red Sandstone of England and Wales is scanty. An inventory of the wells and springs of Herefordshire (Richardson, 1935) provides useful general observations and a reconnaissance-level general resources report study was undertaken by the BGS in 1957 (Richards, 1957). Both are used in this section. Table 9.1 provides a summary of relevant material drawn from the water supply contributions of nine BGS map memoirs, Richardson (1930; 1935) and Monkhouse (1982a, b) to provide yield indications for the Old Red Sandstone outcrop in

Table 9.1 Summary of groundwater flow information on the Old Red Sandstone from BGS memoirs and other published sources.

BGS Map	Author reference	Comments	Typical yields/ranges in m^3/d
166	Greig et al., 1968	Downton Group	Downton Series sandstones yield up to 98 m^3/d; marls up to 76 m^3/d; but generally <33 m^3/d Psammosteus Limestone has many small springs from base and wells yield up to 55 m^3/d
		Ditton Group	Up to 65 m^3/d in lower part and generally >33 m^3/d; exceptionally up to 218 m^3/d
		Farlow and Clee groups	Generally unproductive; Abdon Limestone has small springs at base
182	Mitchell et al., 1962	Downton/Ditton groups	Springs from Psammosteus Limestone. One Ditton Series bore yielded 37 m^3/d
199	Barclay et al., 1997	Raglan Marl Group	Very fracture-dependent; yields 26–60 m^3/d but dry boreholes common; one bore penetrated 354 m and only produced <1 m^3/d from Downton Castle Sandstone below. One exceptional well; 130 m^3/d with Q/s of 43.2 $m^3/d/m$
		St Maughans Formation	Few wells; most yield <43 m^3/d
227	Cantrill et al., 1916	Old Red Sandstone	Many springs around Milford situated along faults or possible fault features. Others mark the junction of Upper and Lower. The Upper ORS is reported to be more jointed. Others on Angle Peninsula are at junction of ORS with Lower Limestone Shales.
228	Strahan et al., 1914	Cosheston Group	Several wells cited as derived from the sandy Cosheston Beds. Springline at the Old Red Marl. Springs said to be common along fractures and faults
229	Strahan et al., 1909	Old Red Sandstone	No mention apart from one spring issuing from ORS at Ferryside
231	Barclay et al., 1988	Old Red Sandstone	No abstractions recorded but water levels close to surface
232	Barclay, 1989	Devonian	St Maughans Formation, Senni Beds, Brownstones and the Upper ORS are locally-used aquifers. Cementation restricts flow mostly to fractures in the weathered zone. Springs issuing from the base of the sandstones commonly yield <10 m^3/d but locally >50 m^3/d. One group of springs in Senni Beds yields >1000 m^3/d. Most boreholes are <30 m depth with mean yields <50 m^3/d but exceptionally >500 m^3/d
249	Squirrell and Downing, 1969	Upper and Lower Old Red Sandstone	Yields of 171–546 m^3/d cited, thought to be from thick sandstones in the sequence. Small supplies from Brownstones and quartz conglomerates of the Upper ORS mentioned. One spring from base of the latter yields 56 m^3/d.
—	Monkhouse, 1982a, b	Old Red Sandstone	(a) Yields mostly <1370 m^3/d (b) A study of 119 boreholes in the ORS of the Welsh Borderland reported boreholes were generally at 50 m depth and from 150 to 250 mm in diameter. Mean specific capacity was about 4.8 $m^3/d/m$ with only a 10% probability of obtaining more than 25 $m^3/d/m$
—	Richardson, 1930	Downtonian	Birch Hill Limestone forms a spring line with porous sandstones above and impermeable marls below. The Holdgate and Downton Castle sandstones yield water
—	Richardson, 1935	Downtonian	Marls predominate; yields generally poor; the Holdgate Sandstone may yield saline water
		Psammosteus Limestone	Notable spring horizon with springs from base
		Dittonian	Sandstone dominated with sandy marls and mudstones; many springs at sandstone/marl junctions
		Quartz Conglomerate Group	Forms spring line; role of formation unclear

general. Qualitative minor information on the Old Red Sandstone in Gloucestershire is also contained in Richardson (1946).

9.2.2.3 *Aquifer properties*

General observations from Environment Agency Welsh Region officers contacted during the data-gathering exercise confirmed that both Upper and Lower Old Red Sandstone sequences are significantly anisotropic and in general these strata appear to behave as a complex, multi-layered aquifer with sandstone bands being hydraulically isolated by intervening mudstones, in the absence of structural features. The effective saturated thickness, for most practical purposes, is taken as 40 m owing to the effect of fracture closure with depth. Pumping test analysis sometimes results in calculated transmissivity values significantly greater than regional estimates, which are typically in the range 10 to 100 m^2/d. This feature is also noted in the Permo-Triassic Sandstones (Allen et al, 1997, 168–169), and has been variously ascribed to:

- interconnection of bedding-plane fractures at local level but not regionally, which could provide apparently higher transmissivity for the relatively short duration of most pumping tests
- connected fracture systems around the well, developed as a result of pumping, forming an extensive (but localised) area of increased fracture transmissivity and improved scope for matrix drainage
- data bias, given that there would be a tendency for pumping tests to be preferentially carried out on those wells showing more promise for production purposes, which would exclude those wells providing insufficient yield to merit equipping with a pump.

Steep regional hydraulic gradients of 0.01 to 0.1 to are said to have been observed, reflecting not only heterogeneity of the fractured aquifer but also the local influence of topography.

9.2.2.4 *Core data*

There are no permeability or porosity measurements in the database for any site on the outcrop area of the Old Red Sandstone of England or Wales. One site, whose location west of Pembroke Dock would probably place the site in the overlying Grey Grits Formation (Upper Devonian) had porosity results for 14 samples taken from less than 35 m depth. These ranged from 1 to 15.3% and averaged 10.2%. Samples from Devonian Old Red Sandstone at depth show low porosity and permeability values (Holliday, 1986) as follows:

- intergranular porosities of up to 20% and permeabilities of up to 0.11 m/d (mean values 16% and 0.013 m/d respectively) were recorded from deltaic Upper Devonian sandstones at Steeple Aston Borehole in Oxfordshire at depths between 837 and 877 m
- porosities of less than 3% and average permeability less than 0.00013 m/d were reported from cores cut from Old Red Sandstone below 1725 m depth in the Marchwood geothermal exploration well near Southampton.

9.2.2.5 *Pumping test results*

There are data available on 200 pumping tests in the Old Red Sandstone. Table 9.2 summarises the distribution of sites by formation, Figure 9.3 shows the location of sites with data and Table 9.3 provides statistics on the collected pumping test results. The formation names used in Table 9.2 are those cited in the individual test descriptors.

Figure 9.4 shows the distribution histogram and cumulative frequency plot of transmissivities for the whole grouping. Eighty seven per cent of records which are stratigraphically non-specific (referring the site generically just to the Old Red Sandstone). Transmissivity values did not

Table 9.2 Distribution of Old Red Sandstone aquifer properties data by cited aquifer for Wales and the Welsh Borders.

Formation	No of tests	No of sites
Old Red Sandstone	174	172
Dittonian Old Red Sandstone	1	1
Raglan Marl	4	4
Lower Old Red Sandstone	18	17
Upper Old Red Sandstone	3	3
Totals	200	197

Table 9.3 Summary of aquifer properties data for the Old Red Sandstone of Wales and the Welsh Borders.

All Old Red Sandstone records		
Total number of records	148	—
Number of transmissivity values	66	—
Minimum/maximum transmissivity value (m^2/d)	0.000001	350
Arithmetic/geometric mean of transmissivity (m^2/d)	51	10.7
Median/interquartile range of transmissivity (m^2/d)	14.3	48.8
25/75 percentile of transmissivity (m^2/d)	4.00	52.8
Number of storage coefficient values	3	—
Minimum/maximum storage coefficient value	1.9×10^{-4}	5.0×10^{-2}
Number of specific capacity values	135	—
Minimum/maximum specific capacity value (m^3/d/m)	0.000001	1226
Arithmetic/geometric mean of specific capacity (m^3/d/m)	39.3	8.29
Median/interquartile range specific capacity (m^3/d/m)	6.59	27.4
25/75 percentile of specific capacity (m^3/d/m)	2.4	29.8

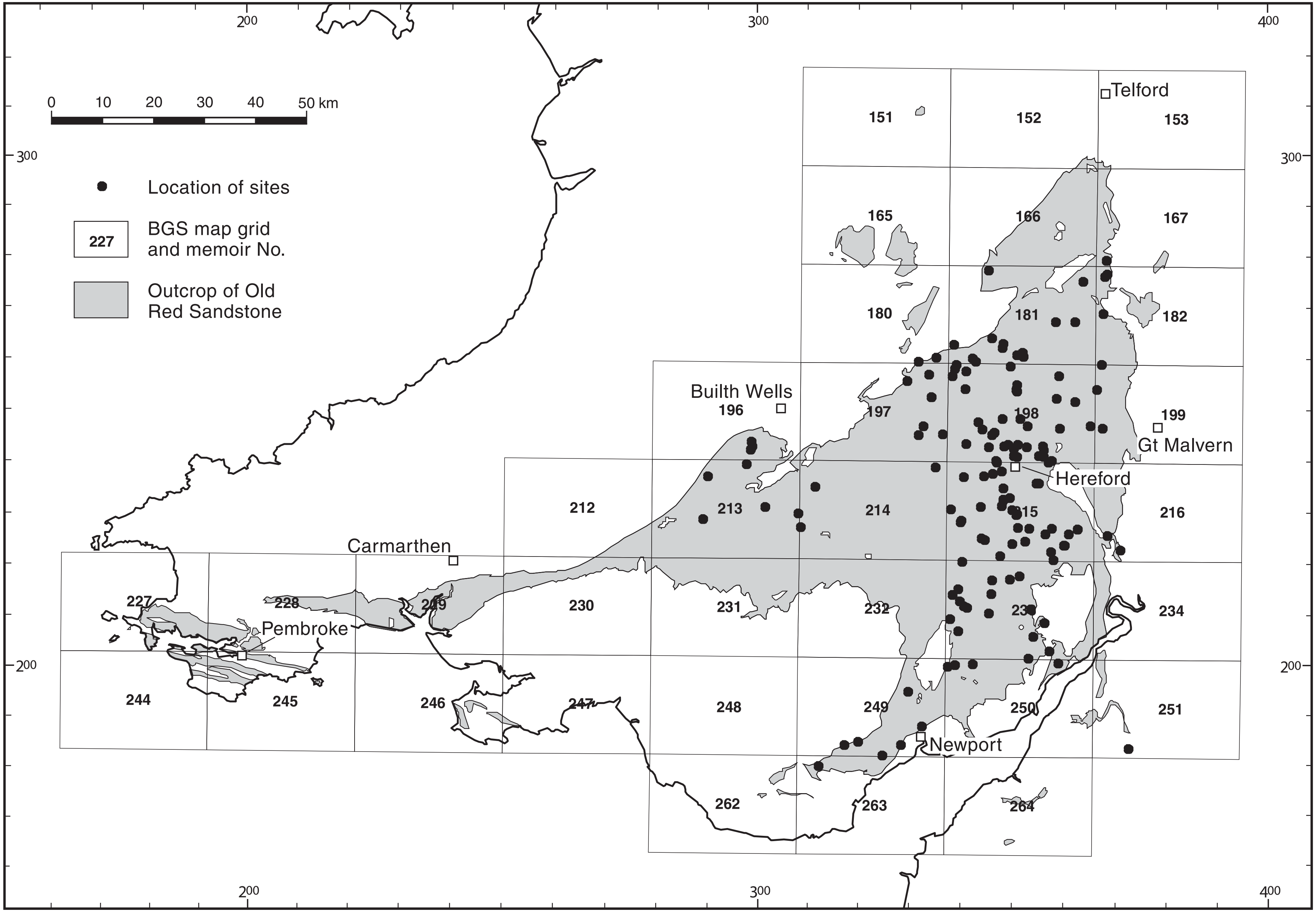

Figure 9.3 Location of Old Red Sandstone sites with aquifer properties data in Wales and the Welsh Borders.

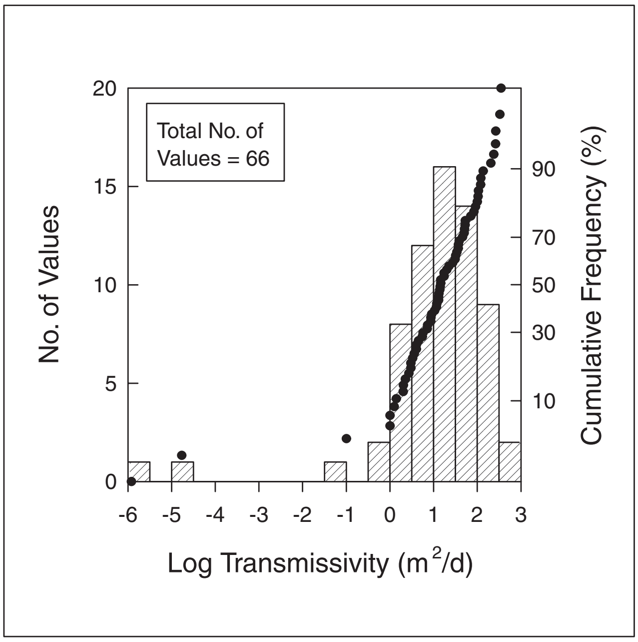

Figure 9.4 Distribution of transmissivity values for the Old Red Sandstone of Wales and the Welsh Borders.

significantly differ between these, and those which specified the site as Upper or Lower Old Red Sandstone. The four sites located on Raglan Marls did record lower values of 4 to 13 m^5/d. The frequency analysis shows that there was only a 10% probability of the value exceeding 225 m^5/d or being less than 2 m^5/d, a surprisingly narrow range considering the thickness, heterogeneity and dominance of fracture flow in the formation as a whole.

The paucity of storage coefficient data does not permit any conclusions to be drawn, although it is noted that the three values collected are in the semi-confined to unconfined range.

Figure 9.5 shows transmissivity plotted against specific capacity (not normalised) for sites in the Old Red Sandstone of Wales and the Welsh Borders. It shows that there is a positive correlation between transmissivity and specific capacity.

Figure 9.6. provides the distribution histogram and cumulative frequency plot of specific capacities for the Old Red Sandstone. The values are distributed log-normally. Most values occur in the 1 to 10 m^3/d/m range, but there is an approximately 10% probability of the specific capacity exceeding 81 m^3/d/m or being less than 1.15 m^3/d/m.

9.1.1.6 *Controls on permeability and transmissivity and effect of structures*

The principal controls on permeability and transmissivity of the Old Red Sandstone are lateral and vertical heterogeneity arising from lithology changes, degree of induration/cementation, and extent/depth of fracturing along bedding planes, as joints or in association with faults or bed flexures.

The only published information on the structural relationships imposed on the Old Red Sandstone during Caledonian or Hercynian tectonism refers to the jointing patterns on the flanks of the South Wales Coalfield, where Roberts (1966) observes that the dominant 340Þ joint set in both Upper and Lower Old Red Sandstone formations parallels the master fault direction of north-north-west to south-south-east (see Section 9.2.1.4). Where well developed, of significant areal extent, and coincident with the regional flow direction, the result could be a directional enhancement of permeability.

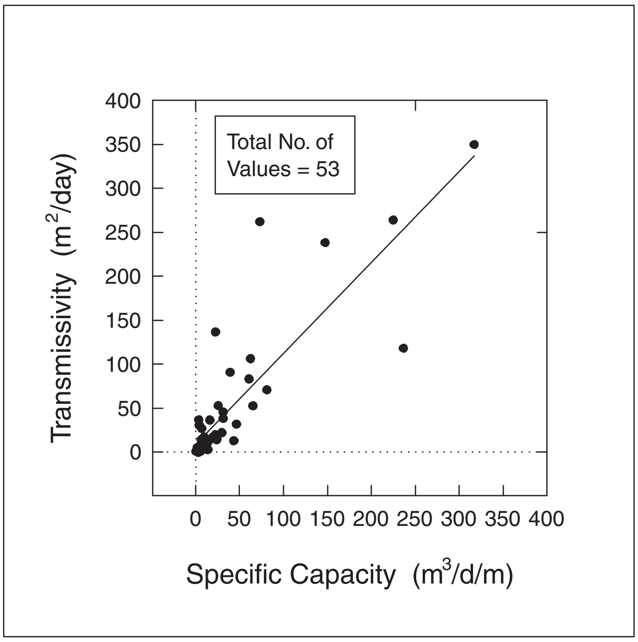

Figure 9.5 Correlation of transmissivity with specific capacity for the Old Red Sandstone of Wales and the Welsh Borders.

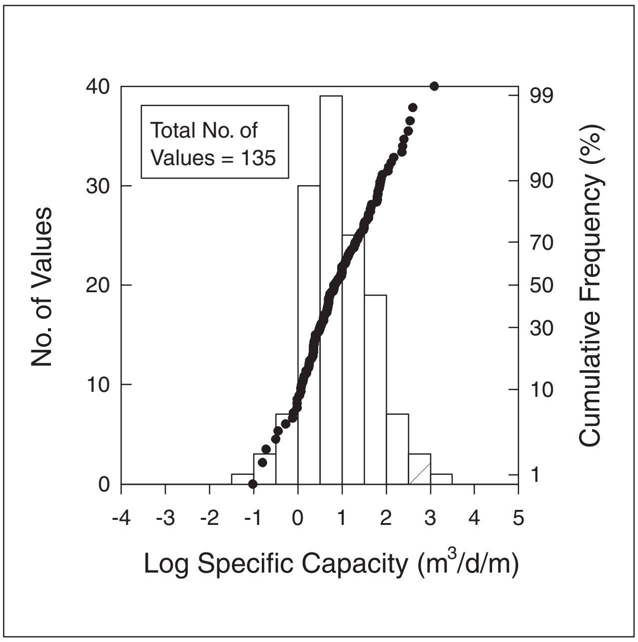

Figure 9.6 Distribution of specific capacity values for the Old Red Sandstone of Wales and the Welsh Borders.

Secondary controls on Old Red Sandstone permeability may arise directly or indirectly from glacial effects due to the presence of the Welsh icesheet during the Pleistocene (D Headworth, personal communication). These may include:

- the effects of depth of burial and subsequent rebound on fracture development. This is likely to be particularly significant for boreholes located close to what was the limit of the glacial front

- shallow bedrock fracture development arising from groundwater circulation, which is affected by the presence or absence of Quaternary glacial deposits, and the deposit type. The depth of such weathering profiles, in turn, will have been affected by changes in base level of erosion since the Pleistocene.

9.3 SOUTH-WEST ENGLAND

9.3.1 Geology and stratigraphy

9.3.1.1 *Extent of aquifer group and stratigraphic relationships*

Devonian outcrops occupy most of the non-granite areas of Cornwall and south Devon south west of a line through Launceston and Dartmoor; the Lizard Peninsula is the only other extensive area of non-Devonian rocks. North of the Devon syncline Devonian strata again emerge from beneath the Carboniferous Culm (deep marine) facies to provide the upland areas of Exmoor, the Quantocks and the Brendon Hills. Five thousand metres or more of strata may be present, but the relationships of the different environments of deposition to one another, and to the Hercynian geosyncline of west Europe are not clear (Dineley, 1992). The rock successions in north Devon, south Devon, north Cornwall, and south Cornwall differ significantly from each other, and appear to have evolved under different tectonic conditions.

The oldest marine strata in Devon and Cornwall are assigned to the Dartmouth Beds (Bluck et al., 1992). The rocks below are unknown, but Precambrian metamorphic basement has been suggested (Cope and Bassett, 1987; Cope, 1988). Carboniferous rocks of the Culm conformably succeed the Devonian rocks of south-west England.

The complex outcrop pattern of Lower, Middle and Upper Devonian rocks in south-west England (Figure 9.1) reflects the intense tectonic history of these marine beds during the Hercynian orogeny compared with the hinterland terrestrial facies of the Old Red Sandstone further north. Figure 9.7 provides a schematic correlation of strata from north Devon to Cornwall, giving an overview of the major differences in thickness and lithological type which occur over the 170 km which span the two main outcrop areas. This is an updated correlation chart, modified from House et al, 1977 to show the current interpretation of the age relationships of strata in the principal outcrop areas.

Such structural complexity in Devon and Cornwall makes estimation of stratal thicknesses difficult. A maximum of 5000 m of strata are estimated to be present in north Devon, while the limestone-dominated sequence at Chudleigh (south-west of Exeter) barely exceeds 200 m, having been deposited over a sharp submarine rise (House, 1975). The simplified facies transect in Figure 9.8 indicates the wide range of lithologies and stratal thicknesses involved.

9.3.1.2 *Lithology and stratigraphy*

Figure 9.9 gives a diagrammatic representation of facies variations in the marine Devonian rocks. In this diagram, Old Red Sandstone facies (fluvial, lacustrine and deltaic sandstones, conglomerates, siltstones and mudstones) are present as terrestrial deposits north of the present Bristol Channel, indicated in the upper part of the figure. The marine facies include both near-shore, shallow marine coarse-grained sandstones, siltstones and shales with a few detrital limestones, and deep-water, basinal shales and limestones, reef carbonates and carbonate turbidites. This reconstruction is an attempt to clarify the often complex field relationships hinted at in Figure 9.8.

Lower Devonian

The Dartmouth Beds consist predominantly of continental, fresh water argillites, with some volcanic rocks. They are subdivided in south Devon into the Warren Sandstones (sandstones and clay-slates with a few conglomerates); Yealm Formation (slates, siltstones and sandstones with many pyroclastic beds); Scobbiscombe Sandstones (sandstones and grits); and Wembury Siltstones (shaly slates, siltstones, conglomerates and silty sandstones). The Bovisand Formation (formerly the Meadfoot Beds) of Cornwall consist of shallow marine slates, siltstones and sandstones with rare but persistent limestones. Coarse agglomerates and tuffs are also present. The Staddon Grits of Cornwall consist of sandstones, intraformational conglomerates and thin limestones. The Lynton Beds are the oldest Devonian representative in north Devon. They are shallow marine bioturbated, fine-grained, laminated sandstones and mudstones with thin shell beds.

In south-west Cornwall, the Veryan Series comprises breccias and conglomerates interbedded with greywackes, slates and limestones.

Middle Devonian

The Staddon Grits in Cornwall are eventually succeeded by the basinal Trevose Slates, with some volcanic lavas and tuffs. Around Plymouth, Torquay and Chudleigh in south Devon are thick, coral-rich limestones (the East Ogwell, Chercombe Bridge, Torquay, Brixham and Plymouth limestones).

In north Devon and Somerset, the Hangman Grits are mainly fluvial and deltaic clay-slates, sandstones and conglomerates. There are some marine strata in the upper parts. The overlying Ilfracombe Beds comprise marine slates with thin limestones and sandstones and slates of probable shallow marine and deltaic origin.

In central Cornwall, the Upper and Lower Gramscathos Beds (now termed the Carne and Portscatho formations respectively) comprise a heterogeneous array of interbedded greywackes and slates with sporadic limestones, conglomerates, cherts and spilitic lavas. These are thought to span the Upper/Middle Devonian boundary.

Upper Devonian

The Morte Slates of north Devon are smooth, glossy, grey and purple slates with scattered calcareous nodules and thin, shallow marine sandstones. The succeeding Pickwell Down Beds comprise red, purple, brown and green sandstones of Old Red Sandstone facies, with some grey-blue shales. The Upcott Beds are yellow and green, cleaved sandstones and slates, succeeded by the deltaic sandstones and siltstones of the Baggy Beds. The overlying Pilton Beds are fossiliferous, blue-grey slates and limestones with cross-bedded sandstones.

The Mylor Slates are also flysch-type deep water slates and greywackes. In south Devon, ostracod-rich slates (e.g. the Gurrington Slate and Whitway Slate) are bluish, purple and green deep-water deposits.

The Upper Devonian rocks of west Cornwall are represented by grey and purple slates.

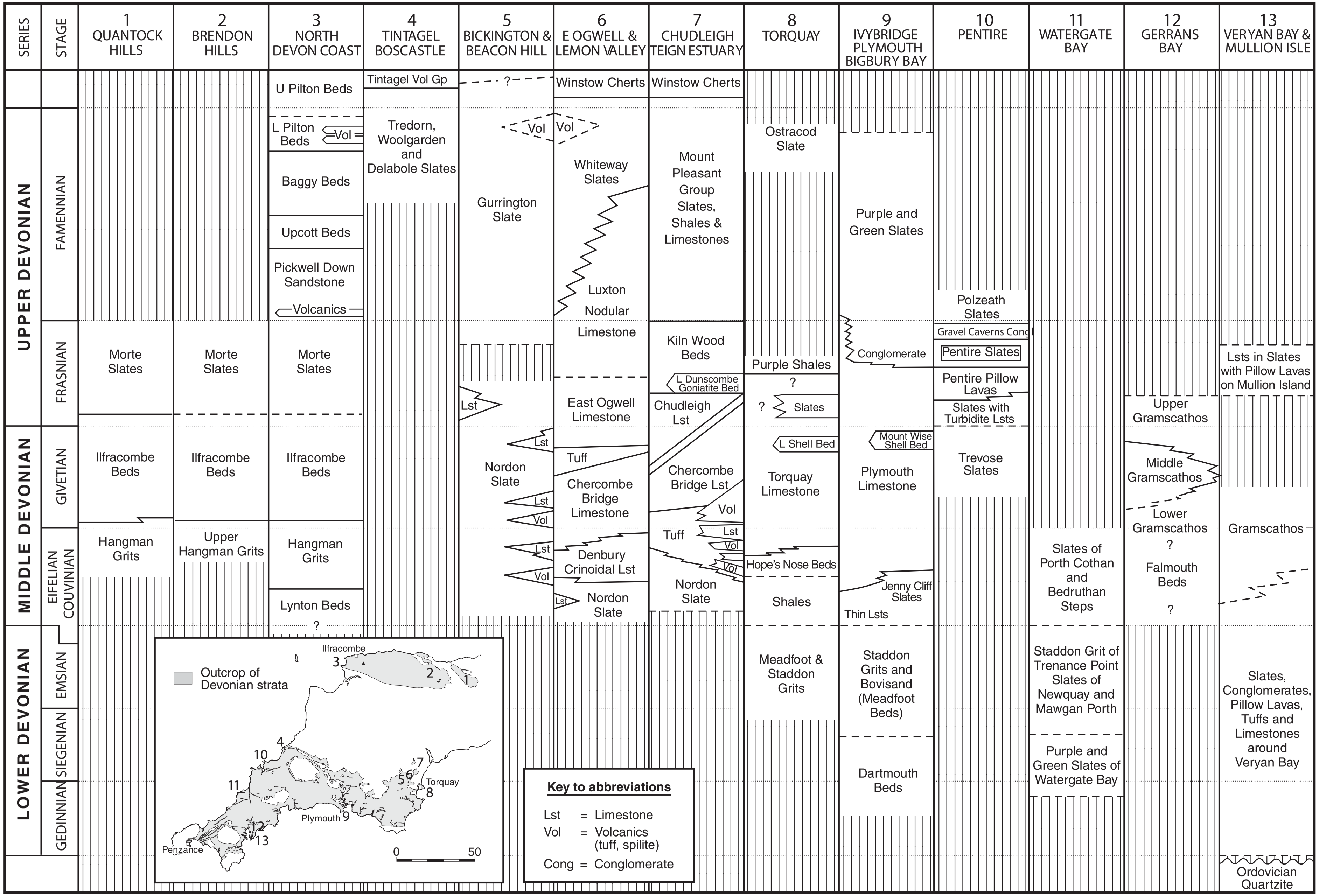

Figure 9.7 Selective correlation of Devonian stratigraphy in south-west England (modified from House et al., 1977; Allen et al., 1982).

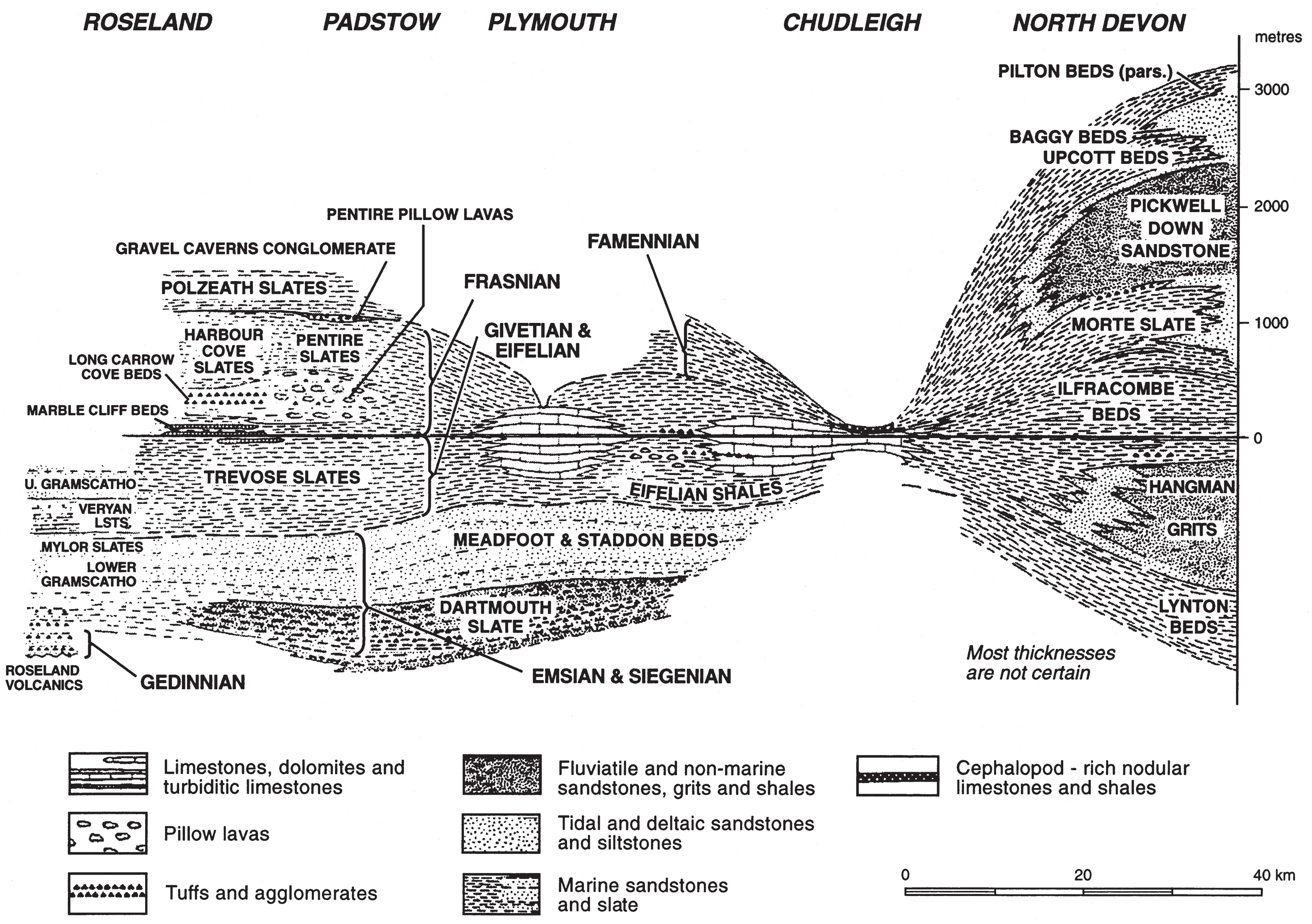

Figure 9.8 Facies and stratal thickness variations in the Devonian of south-west England (after House et al., 1977).

9.3.1.3 *Structural and depositional history*

Hercynian orogenic deformation consisted of north–south compression, which resulted in shallow thrust-folding and faulting of the marine facies of Cornwall and Devon against the Wales/Brabant High (Figure 9.9). This produced a large compound syncline in central Devon, flanked on the north by an east–west-trending anticlinorium with divergent-facing folds thought to be of late Carboniferous age. To the south in central Cornwall and south Devon, the folding is northward-facing with the recumbent folds having a slaty cleavage which dies out northwards. This folding is considered to be of early Carboniferous age. In south Cornwall the thrusts and folds have a north-east trend, and are thought to be of late Devonian age. They are present as nappe structures, as in the Lizard Complex. Thus the deformation is considered to have migrated northwards with time.

The great diversity of lithologies (from arenites through argillites to limestones), complex post-depositional structural deformation, and local/regional metamorphism with associated mineralisation, all combine to render comments on jointing, cementation and porosity no more than qualitative. There are no published studies or known readily

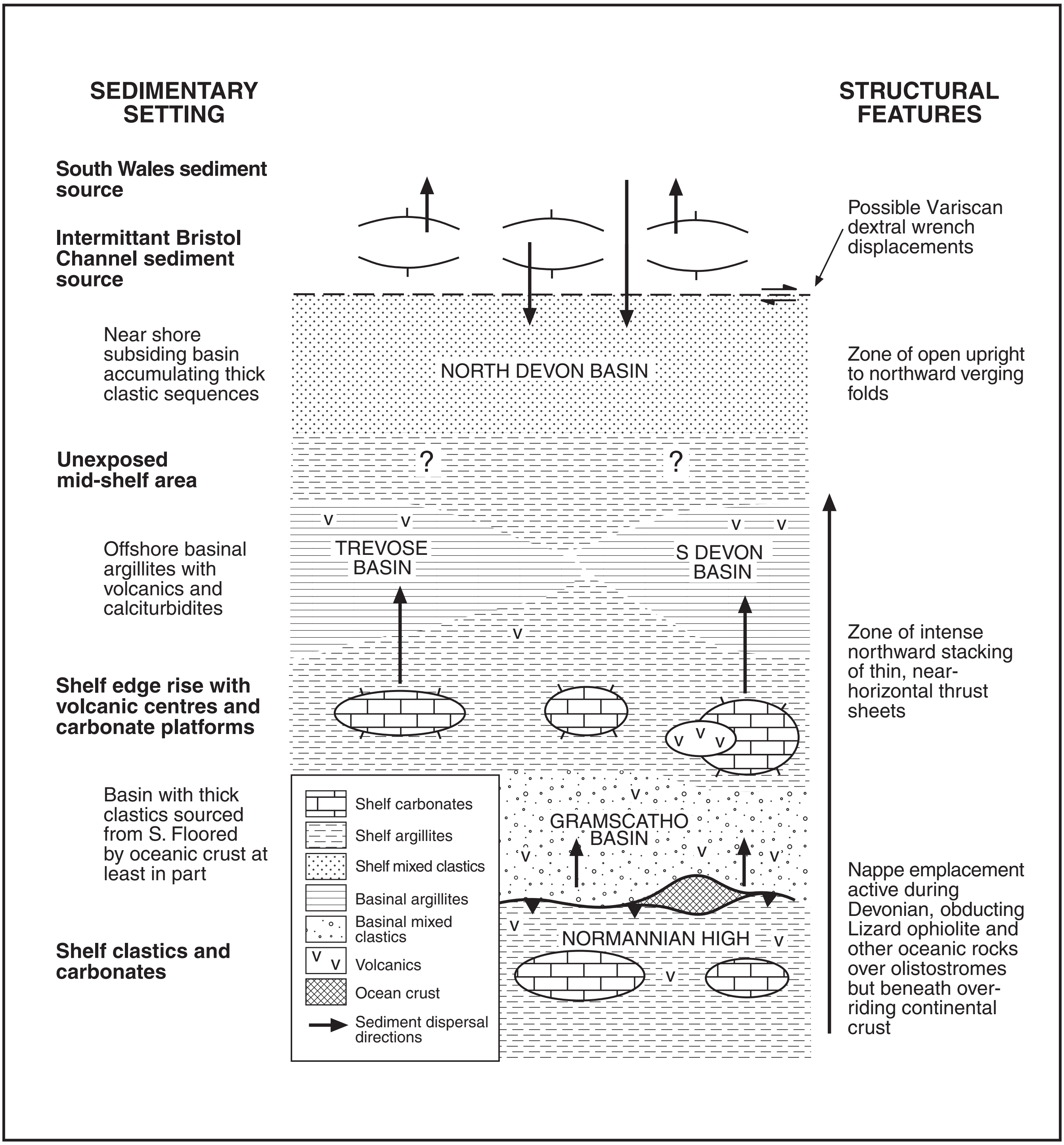

Figure 9.9 Possible distribution of main sedimentary basins and the tectonic setting of south-west England during the Devonian (after Bluck et al., 1992, fig. 1).

accessible data on the subject for the Devonian of south-west England. In general terms, like most hard-rock terrains, the marine slates, siltstones. greywackes and associated volcanic lavas and tuffs have low primary porosities. The sandstones are compact and well cemented, and the limestones are dense and highly crystalline. Thus, permeability is dependent on the extent of development of secondary fracture features such as jointing and cleavage.

9.3.1.4 *Igneous activity*

Intrusions of Devonian age are not known, but as igneous activity during the Lower Palaeozoic was controlled by Hercynian tectonics, Devonian sediments and associated extrusives have been affected by the emplacement in late Carboniferous times of the granite batholith of south-west England. This followed the final compressional phase of the Hercynian orogeny and provided localised transformations of host rock properties through contact metamorphism and metasomatic mineralisation.

Volcanic activity occurred throughout the Devonian period in Devon and Cornwall and was mainly submarine. This activity has resulted in agglomerates and tuffs in the Lower Devonian strata, spilitic lavas and tuffs in the Middle Devonian, and pillow lavas at the start of the Upper Devonian. All show extensive alteration due to low-grade (greenschist facies) regional metamorphism and contact metamorphism in the granite aureoles.

9.3.2 Hydrogeology

9.3.2.1 *Introduction*

Ussher (1933) commented that, in the Torquay area, structure rather than lithology dictates yields; this comment could be applied to the rest of the Devonian succession of south-west England. This is because primary porosity is an insignificant contributor to permeability and storage throughout the Devonian succession. Four principal factors explain this observation.

i The sandstone members have low porosity, being compact and well cemented, and their indurated nature is likely to reduce the frequency of fractures compared with less competent shales and slates present elsewhere in the succession. Even the limestones, which are locally quite permeable, as in the Plymouth area, owe their higher yields to the development of karstic secondary permeability features.

ii Although the effects of tectonism are variable across the region, they are nonetheless much more intense than those resulting from the corresponding earth movements affecting the Old Red Sandstone north of the Bristol Channel. Folding ranges in intensity from open southwards through tightly isoclinal to recumbent; there is local development of nappe structures and thrusting in south Devon and south-west Cornwall. Faulting has resulted not only from compression along plate margins but also from the igneous intrusion of the south-west England Batholith. While major faults have only been mapped where they have been observed from bed displacements at the surface, observations from mines exploiting tin mineralisation of the country rock (‘killas’) and the granite plutons themselves provide a generally accepted view that small scale faulting is common.

iii Regional metamorphism, most generally of low-grade regional greenschist facies, has imposed cleavage which is locally intense enough in argillaceous parts of the succession to produce slates, and elsewhere to contribute to the degree of induration of clastic rock matrices. Additionally, local high-grade contact metamorphism around the granite plutons has not only converted most of the succession into brittle competent rocks (for example by conversion of shales to hornfels), but also has required accommodation faulting during emplacement of the intrusion. These processes may explain the observation that the aureoles are generally more water-bearing than their less-metamorphosed country rock equivalents.

iv Where the carbonate rocks have been deposited, as in the condensed succession of south Devon, karstic solution effects have produced a secondary porosity in limestones which are otherwise dense and highly crystalline. This has arisen from localised solution of a dense, well recrystallised matrix along structurally-initiated fracture systems.

The general effect has been to reduce the difference in flow and storage characteristics between geologically quite distinct rock types but to increase the frequency of variability of the succession as a whole regardless of the dominant lithology in an area.

9.3.2.2 *Previous studies*

There is little published material of hydrogeological interest on the Devonian aquifers of south-west England. Some commentary is found in the water supply contributions of the BGS geological map memoirs of the region, with the older memoirs tending to be qualitative or superficial. Table 9.4 is a compilation of extracts of relevant comments with some cited yield ranges. Inglis (1877) and Roxburgh (1983) commented on hydrogeological aspects of the limestones in and around Plymouth. Sherrell (1969) provides an account of a saline intrusion problem in Middle Devonian slates at Brixton east of Plymouth

9.3.2.3 *Core data*

No core information was found for any Devonian strata in south-west England.

9.3.2.4 *Pumping test results*

Aquifer properties information has been derived from the approximately 160 pumping tests recorded for the Devonian of south-west England. As the Palaeozoic stratigraphy of the region is both complex and subject to ongoing revision, the sites have been treated for statistical purposes both together (as set A, all Devonian of south-west England) and as subsets B, C, and D on a much-simplified lithological basis (as predominantly arenaceous, carbonate or argillaceous respectively). The subsets were chosen and analysed on parent lithology in order to test whether the formations' aquifer properties, while tectonically/structurally controlled, may also show sediment type effects. Table 9.5 summarises the divisions and Figure 9.10 shows the locations of sites.

The results of the statistical analysis of the data are summarised in Table 9.6 and shown as comparative graph sets

Table 9.4 Summary of groundwater flow information on Devonian aquifers of south-west England from BGS memoirs and other published sources.

BGS Map	Author ref	Formations commented upon	Typical yields/ranges in m^3/d or other comments
276, 292	Edmonds et al., 1979	Upper Devonian	Morte Slates, Upcott Beds and Pilton Shales; low permeability and storage; flow depends on fractures and shatter belts. Pickwell Down and Baggy sandstones, better potential; cited Q/s of 1.8 m^3/d/m and yields of 33–66 m^3/d
277,293	Edmonds et al., 1985	Upper Devonian	Ilfracombe and Morte Slates, Upcott Beds, Pilton Shales, low permeability; moderate initial yields often not sustained as interconnected fracture systems dewater. Typical yields 27–43 m^3/d. Hangman Grits, Pickwell Down and Baggy Ssts have some potential fractures (matrix is strongly cemented). Typical yields 27–76 m^3/d but up to 227 m^3/d in one case
295	Edmonds and Williams, 1985	Upper Devonian	Hangman Grits, cited yields of 46 and 545 m^3/d. Morte Slates, up to 49 m^3/d. Pilton Shales, up to 27 m^3/d
335,336	Selwood et al., 1998	Devonian and Carboniferous jointly	Mean yield of 65 boreholes in Devonian and Culm of district was 52 m^3/d with 20% probability of yields <26 m^3/d. One exceptional yield of 199 m^3/d reported from Middle Devonian slates
339	Selwood et al., 1984	Devonian slates Middle Devonian limestones	Maximum recorded yield 121 m^3/d Locally punctuated by extensive solution channels and yields thought to be potentially >>78 m^3/d which is the recorded maximum
346	Reid and Scrivener 1906	Thermally altered Devonian sediments	Considered more productive than those outside the zone of contact metamorphism. Historically Newquay's public supply was from disused mine adits draining the aureole surrounding the St Austell granite
347	Ussher et al., 1909	Thermally altered Devonian sediments	Numerous springs reported to drain from aureole of Bodmin granite; Bodmin historically supplied from these springs
348	Leveridge et al., 1997	Plymouth Limestone & Devonian (various)	Mean of licensed abstractions was calculated for different formations; Dartmouth Slates 3.8 m^3/d (18 sources) Bovisand Formation 3.7 m^3/d (20 sources) Staddon Formation 6.4 m^3/d (10 sources) Saltash Formation 3.7 m^3/d (51 sources) Torpoint Formation 8.1 m^3/d (8 sources) Tavy Formation 4.8 m^3/d (35 sources) Springs reported to issue from Saltash/Torpoint Formation junction. Plymouth Limestone is dense and well recrystallised but has karstic solution features; best yields reported along faulted junction with the slates. Former brewery and spa yields of up to 654 m^3/d and other former industrial supplies up to 1200 m^3/d with a Q/s in one case of 800 m^3/d/m. Limestone horizons within both the Saltash and Torpoint formations can provide above-average yields if solution features encountered. Sustained yields from slates and grits reported as difficult
350	Ussher, 1933	Devonian grits and volcanics	Strong springs may rise from limestone/shale boundaries. Lower Devonian grits reported as too compact for good yields. Structure not lithology dictates yields. Totnes was historically (1930) supplied by springs from Devonian tuffs and lavas (500 m^3/d)
352	Leveridge et al., 1990	Thermally altered Devonian sediments	Average of yields 34 m^3/d with 20% probability of <22 m^3/d
Map	Institute of Geological Sciences and South West Water, 1982	Devonian	Borehole yields generally less than 43 m^3/d. Fault-bounded limestones in Torquay and Newton Abbott areas form locally important karstic aquifers. Springs common at junction of Middle Devonian limestone and underlying shale around Torquay

in Figures 9.11A, B and C for transmissivity, Figures 9.12.A and B for storage coefficient and in Figures 9.13 A, B, and C for specific capacity.

For the Devonian of south-west England as a whole, the interquartile range of transmissivity is from 1 to 17 m^2/d. There is about a 3% possibility that the transmissivity exceeds 150 m^2/d; these higher transmissivity values are attributable to the effects of fracturing. The broad spread of transmissivities in the undivided set is reflected in the arenaceous and argillaceous subsets, whose median, 25 percentile and 75 percentile values are similar. However, the geometric mean of set B (arenaceous strata) is two orders of magnitude less than those of the full dataset and the argillaceous strata; the reasons for this are not clear.

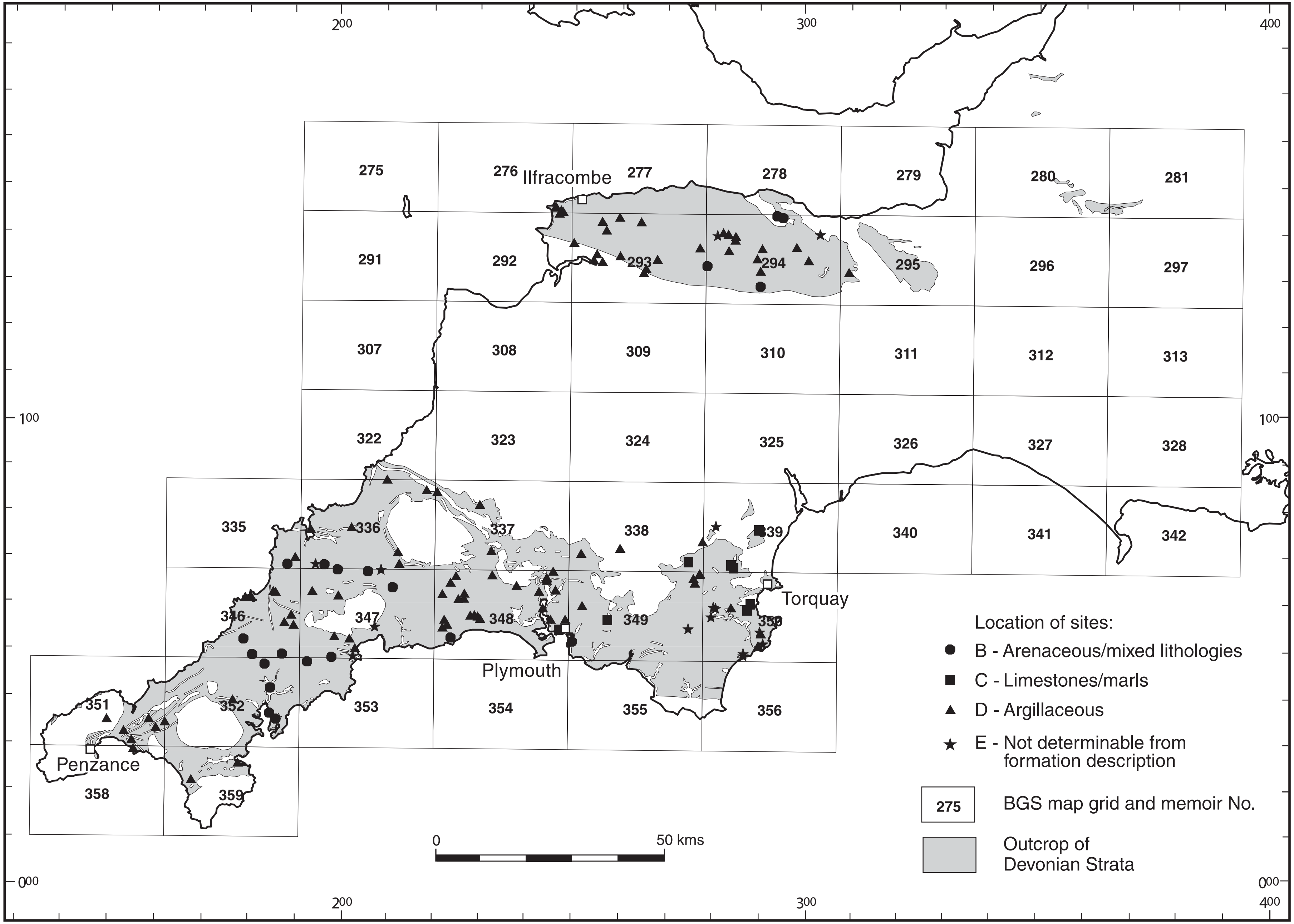

Figure 9.10 Location of sites with aquifer properties data in the Devonian of south-west England.

Table 9.5 Distribution of aquifer properties data in south-west England by dominant lithology.

Formation grouping	Set	No of tests with data	No of sites
All Devonian of south-west England	A	159	184
Arenaceous, or mixed including arenaceous	B	25	20
Limestones and marls	C	13	12
Argillaceous including shales, slates, greywackes, mudstones, siltstones	D	103	134
Not determinable from formation description	E	18	18

Table 9.6 Summary of aquifer properties data for the Devonian aquifers of south-west England.

Parameter	Set A All Devonian sites		Set B Arenaceous/mixed		Set C Limestones/marls		Set D Argillaceous	
Total number of records	170	—	22	—	9	—	72	—
Number of transmissivity values	107	—	16	—	7	—	50	—
Minimum/maximum transmissivity value (m^2/d)	0.000004	247	0.4	36.5	1.0	247	0.1	177
Arithmetic/geometric mean of transmissivity (m^2/d)	15.6	4.0	9.1	0.04	46.4	13.7	10.7	3.5
Median/interquartile range of transmissivity (m^2/d)	4.0	16.0	4	14.4	17.9	39.4	3.3	9.9
25/75 percentile of transmissivity (m^2/d)	1.0	17.0	1.0	15.4	7.5	47.0	1.0	10.9
Number of storage coefficient values	30	—	6	—	1	—	11	—
Minimum/maximum storage coefficient value	7.7×10^{-7}	0.9*	0.019	0.3	4×10^{-4}	4×10^{-4}	7.7×10^{-7}	0.9*
Number of specific capacity values	163	—	21	—	8	—	69	—
Minimum/maximum specific capacity value (m^3/d/m)	0.1	9101	0.9	56.7	2	801	0.5	1600
Arithmetic/geometric mean of specific capacity (m^3/d/m)	118	9.7	15.1	7.4	131	31.2	45.1	6.6
Median/interquartile range of specific capacity (m^3/d/m)	7.5	28.4	7.9	19.9	27.8	78.5	4.5	13.7
25/75 percentile of specific capacity (m^3/d/m)	2.7	31.1	3.8	23.7	10.9	89.4	2.2	15.9

* recorded but spurious value

Table 9.6 shows that the limestones tend to have typically a slightly higher transmissivity than the other lithologies, evidenced in greater geometric mean, 25 percentile and 75 percentile. This is presumably a reflection of better-developed fracture interconnectivity due to solution. These results are consistent with commentary in BGS memoirs referring to higher than average yields in Middle Devonian Limestones (e.g. Plymouth Limestone in Ussher, 1907 and Leveridge et al., 1997).

There are relatively few storage coefficient values but the majority tend to be in the unconfined range, typically showing specific yields of 0.01 to 0.3, although the dataset is small and possibly skewed. Semi-confined and confined values of 10 to 3 or less are rare. This may be a data artefact in that the wells are often relatively low-yielding so tests are generally of short duration and the effects of fracture system dewatering may not be detected.

For all the data, the interquartile range of specific capacities is 3 to 31 m^3/d/m. These data also show little difference between sandstone and shale/slate-dominant formations, but again the limestones typically have higher specific capacities. Their geometric mean is four times that of the arenaceous and argillaceous subsets and both the 25 percentile and 75 percentile values are higher. The differences however are not marked.

There is a good correlation between specific capacity and transmissivity both for arenaceous and argillaceous subgroups (see Figures 9.14a, b and c). When all data are used, however, the correlation between transmissivity and specific capacity is poor. This is probably due to the effects on the statistics of sites in the limestones where very high specific capacities can occur if productive fissure-flow systems are encountered.

These comments should be considered in the light of the limited data available for the limestones/marls (seven transmissivity values, eight specific capacity values).

9.3.2.5 *Controls on permeability and transmissivity*

Jointing and cleavage, which provide the principal controls on matrix permeability, are well developed in the Devonian strata of south-west England, because of the intense folding present in the Devonian south of the present Bristol Channel. This has stimulated the development of axial plane cleavage systems. Where such cleavage patterns intersect bedding planes, there are opportunities for groundwater flow along interconnected fracture systems, at least at shallow depths of a few tens of metres where the fractures have not closed or become mineralised.

Other fracture systems occur in tight folds, due to the development of radial joints around the crests of anticlines and rotation joints along the limbs. As these fractures are tensional, they may remain open (see Figure 9.15 (after Price, 1966)). Thinly bedded sequences of alternating brittle and semi-brittle rock would be expected to show particularly well-developed fractures of this type because of the accommodation slippage occurring between individual horizons.

A further control on the flow of water through these formations lies in the extent and nature of the faulting. Evidence from mining shows faulting to be much more common than can be deduced from study of the outcrop. Even so, it may be that faulting only plays a comparatively minor part because the tectonic environment during the dominant (Hercynian) cycle was one of compression from plate movements and displacement from igneous intrusion. For

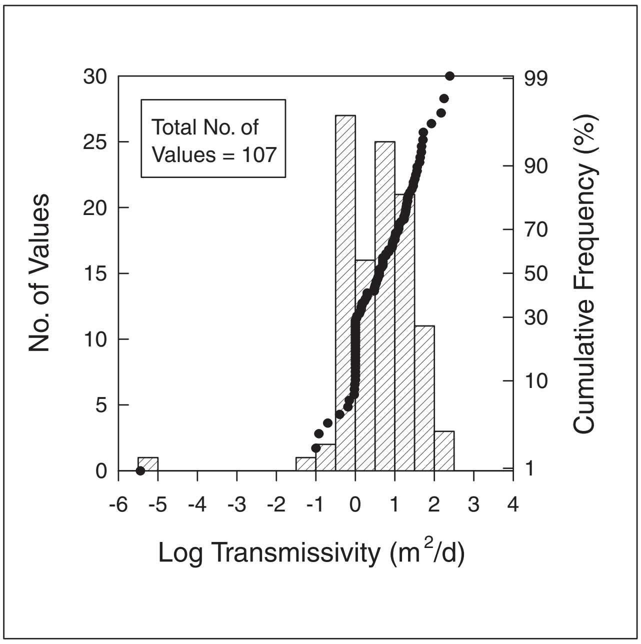

Figure 9.11a Distribution of all transmissivity values for the Devonian aquifers of south-west England.

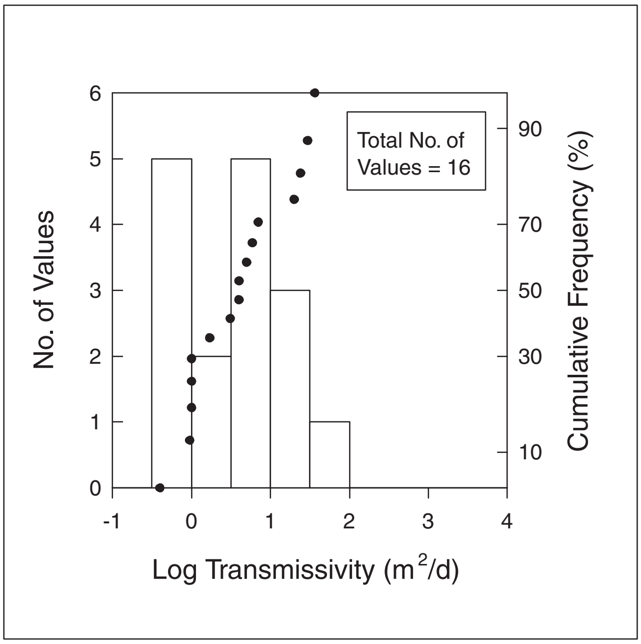

Figure 9.11b Distribution of transmissivity values for the arenaceous Devonian aquifers of south-west England.

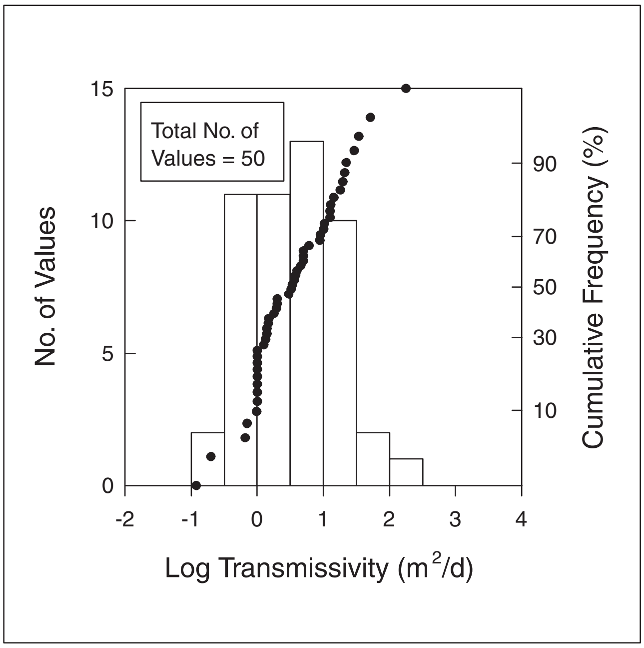

Figure 9.11c Distribution of transmissivity values for the argillaceous Devonian aquifers of south-west England.

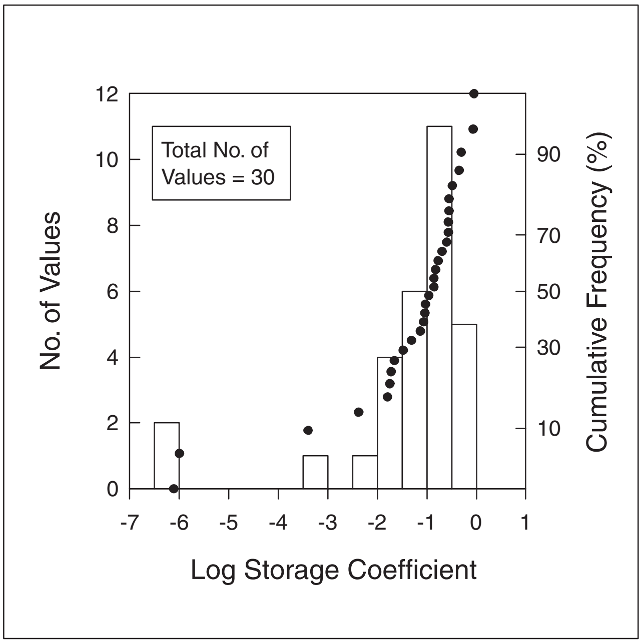

Figure 9.12a Distribution of all storage coefficient values for the Devonian aquifers of south-west England.

instance, thrust faulting zones, which are common, being a compressional stress release mechanism, are unlikely to contribute to secondary porosity because the fault planes remain closed and shear faces are often accompanied by granulation and smearing of minerals.

Finally, an additional local control on flow is likely to arise from enhanced jointing in the sedimentary formations of the granite aureoles, where contact metamorphism would make the rocks more prone to brittle fracture. Furthermore, the intrusion process would have been accompanied by structural displacement and dislocation.

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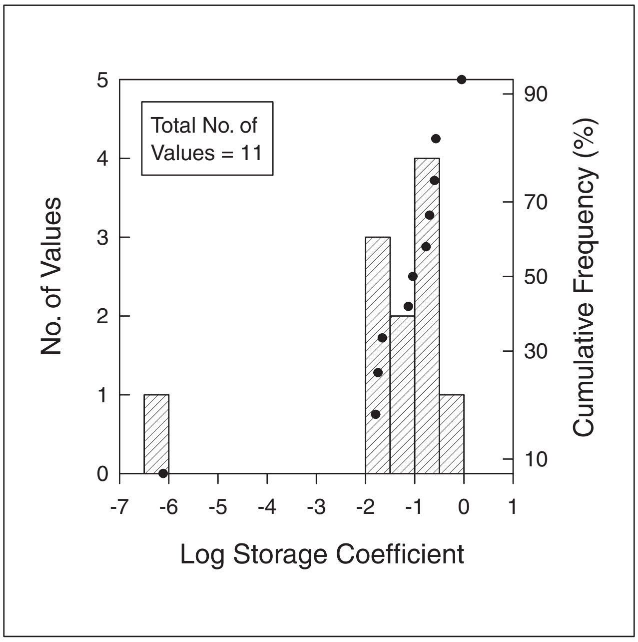

Figure 9.12b Distribution of storage coefficient values for the argillaceous Devonian aquifers of south-west England.

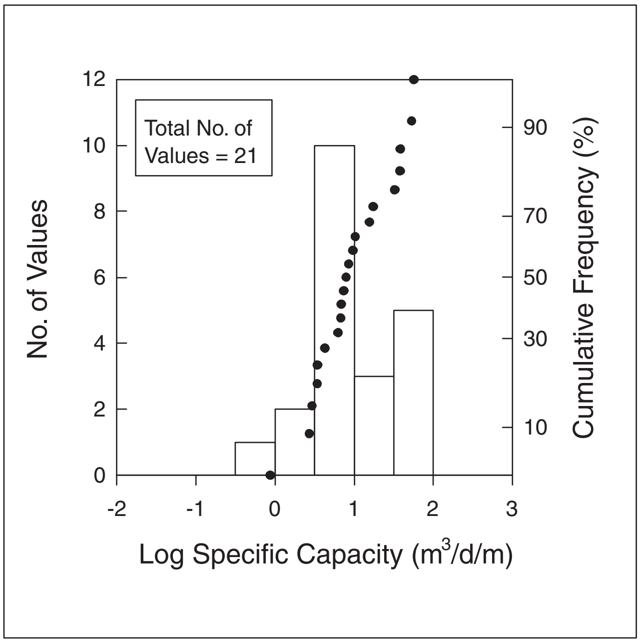

Figure 9.13b Distribution of specific capacity values for the arenaceous Devonian aquifers of south-west England.

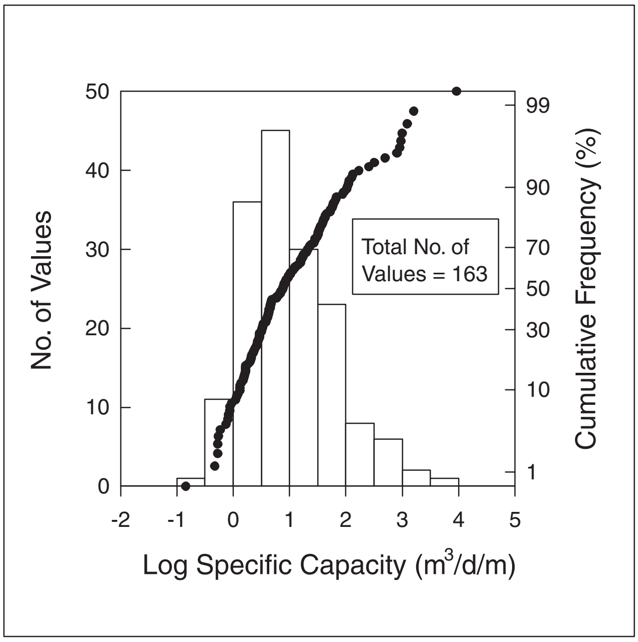

Figure 9.13a Distribution of all specific capacity values for the Devonian aquifers of south-west England.

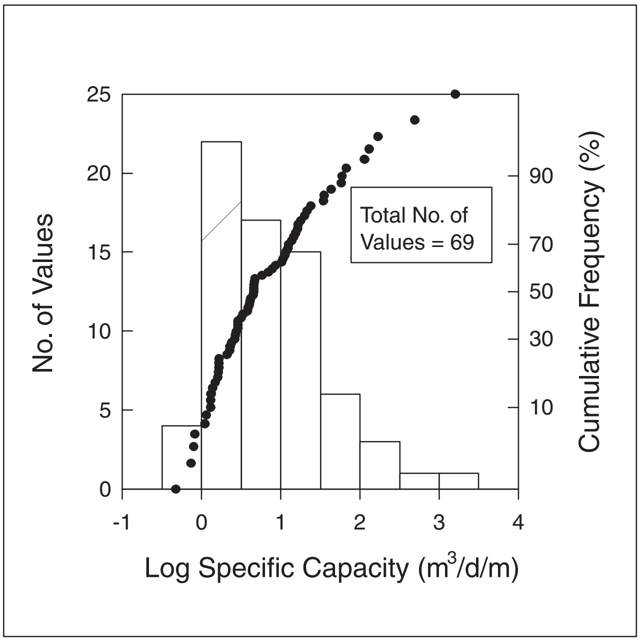

Figure 9.13c Distribution of specific capacity values for the argillaceous Devonian aquifers of south-west England.

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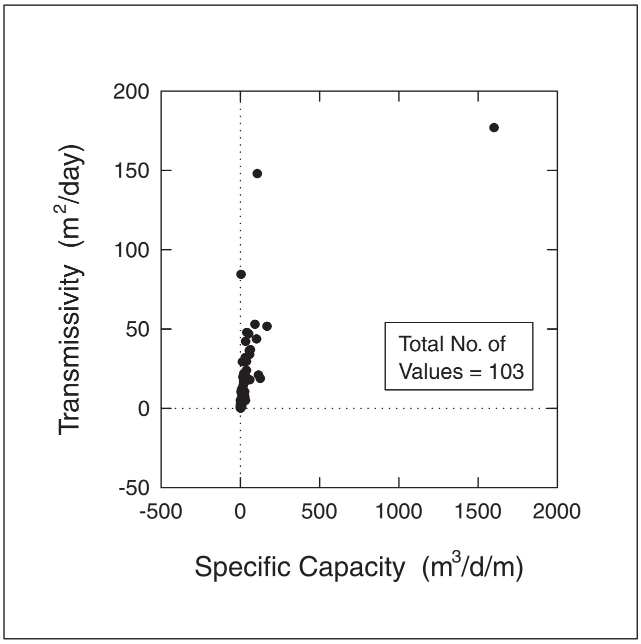

Figure 9.14a Correlation of transmissivity with specific capacity for all the Devonian aquifers of south-west England.

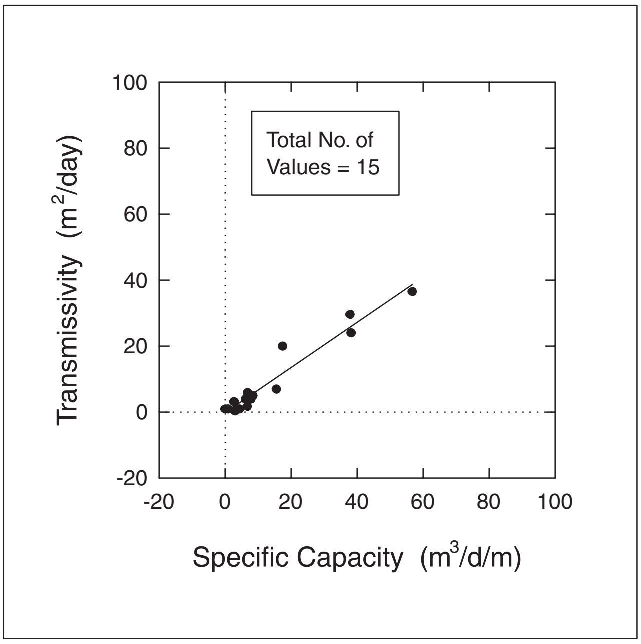

Figure 9.14b Correlation of transmissivity with specific capacity for the arenaceous Devonian aquifers of south-west England.

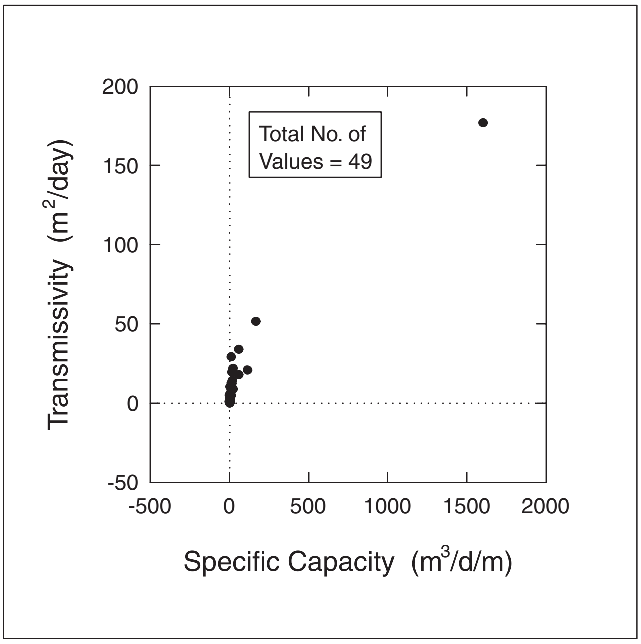

Figure 9.14c Correlation of transmissivity with specific capacity for the argillaceous Devonian aquifers of south-west England.

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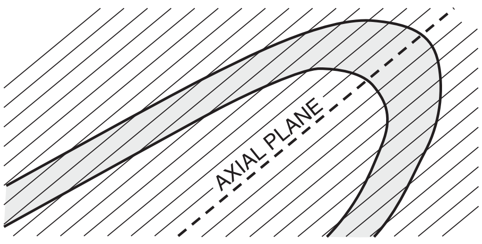
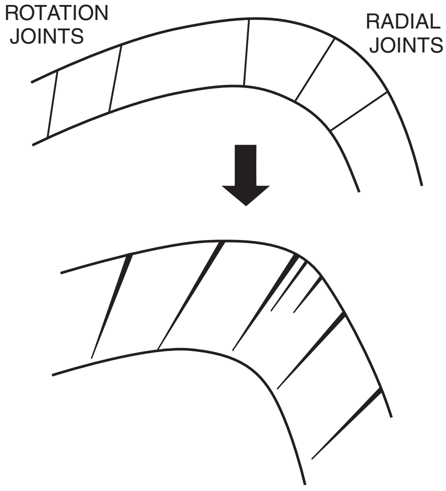


The relationship of axial-plane cleavage to bedding (After Bennison, 1969)



Section of crest of anticline showing typical orientations of radial joints about the crest, and rotation joints in the gentle dipping limb. These flexural tension joints may remain open or become mineral-filled (After Price, 1966)

Figure 9.15 Examples of how deformation features can enhance secondary porosity and improve flow of groundwater in hard-rock aquifers.

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10 Pre-Devonian and igneous minor aquifers

10.1 INTRODUCTION

The pre-Devonian minor aquifers of England and Wales as described in this chapter include all Lower Palaeozoic and Precambrian rocks of sedimentary, metamorphic and volcanic origin, since these rock types have similar hydrogeological characteristics despite their various origins. Igneous intrusive rocks, principally the granites of south-west England, are also included in this chapter. The summary stratigraphy of the pre-Devonian strata, and age relationships of the hydrogeologically important igneous strata are shown in Table 10.1.

Areas of pre-Devonian and igneous strata typically comprise sparsely populated uplands, often receiving high rainfall. Water supplies are therefore readily available from surface sources or springs, so the widespread development of groundwater resources by the construction of wells and boreholes has not been required. As a result, data for these aquifers are sparse. This is especially the case for the areas of metamorphosed rocks in England and Wales, for which as a class hydrogeological information is to all intents and purposes absent.

It should be noted that dry and very low yielding boreholes are frequently not represented in the data sets. It is therefore considered that an inherent bias exists within the data, in that there would be a tendency for pumping tests to be preferentially carried out on higher yielding wells showing more promise for production purposes. Thus the lower values of yield, transmissivity and specific capacity are more likely to be representative of 'average' aquifer characteristics. Similarly, it should also be noted that although dry and very low yielding boreholes have undoubtedly been drilled, such boreholes would not by definition be included in a pumping test data set.

Table 10.1 Summary stratigraphy of the pre-Devonian strata, and age relationships of the hydrogeologically important igneous strata.

SEDIMENTARY AND IGNEOUS EXTRUSIVE				IGNEOUS INTRUSIVE	
UPPER	PALAEOZOIC	PERMIAN CARBONIFEROUS DEVONIAN		↑	Cornubian Granite Batholith
LOWER		SILURIAN	Prídolí Series Ludlow Series Wenlock Series Llandovery Series	Lizard Complex	
		ORDOVICIAN	Ashgill Series Caradoc Series Llandeilo Series Llanvirn Series Arenig Series Tremadoc Series		Leicester Diorite
		CAMBRIAN	Merioneth Series St. David's Series Comley Series		
PRECAMBRIAN				↓	

10.2 PRE-DEVONIAN

10.2.1 Introduction

Strata of Lower Palaeozoic age outcrop over much of the Lake District, northern and central Wales and as small inliers in the West Midlands and the Mendips. The distribution of these strata is shown in Figure 10.1, together with the more limited outcrops of Precambrian strata. Although there are other pre-Devonian rocks present at depth, and less commonly elsewhere as patchy outcrops, in England and Wales, little or no aquifer physical properties data were identified for these areas.

The rocks are well cemented and indurated, and hence aquifer properties are strongly influenced by fracturing, and to some extent weathering.

Limited aquifer properties data are available for these rocks, and have been supplemented through examination of the National Well Record Archive data held by the BGS.

10.2.2 Geology and stratigraphy

10.2.2.1 *Precambrian and Cambrian*

Late Precambrian to early Cambrian island-arc volcanism is evident in the numerous small inliers of Precambrian rocks at outcrop across England and Wales.

The volcanic rocks of the Mona Complex of north-west Wales are typically basaltic and include pillow lavas as well as basic, intermediate and acidic tuffs and volcaniclastic sedimentary rocks. The youngest rocks include lavas and acidic pyroclastic flows. The sequence also includes gneisses, turbidites and quartzites towards the base and grits and shales in the upper part. The rocks of the Mona Supergroup are intruded by the Coedana Granite and later by aplitic veins, also of Precambrian age. Small (around 3 km long) ultramafic and mafic intrusive bodies, locally present on Holy Island (Anglesey) are altered to serpentinites and metagabbros. The Mona Supergroup is overlain by 'Arvonian' strata including andesites, dacites and rhyolites with acid pyroclastic rocks including ignimbrites, considered to be late Precambrian to early Cambrian in age. These strata have been intruded by a 4 km^2 granite and felsite veins.

In the vicinity of St. Davids, in south-west Wales, the Pebidean Volcanic Group comprises at least 1500 m of lavas and pyroclastic rocks of andesite-rhyolite composition together with volcaniclastic sedimentary rocks. Basic, intermediate and acidic intrusions in the latter are in turn intruded by Precambrian dolerite dykes.

The late Precambrian Malvernian rocks of the Malvern Hills include plutonic intrusions, dominantly diorites and tonalites with subordinate granites and minor ultramafic rocks, in turn intruded by basic dykes and trachytes. On the eastern flank of the Malvern Hills is a small area, (about 1 km^2), of basic to acidic lavas and pyroclastic breccias, tuffs, and pyroclastic flow deposits of the Warren House

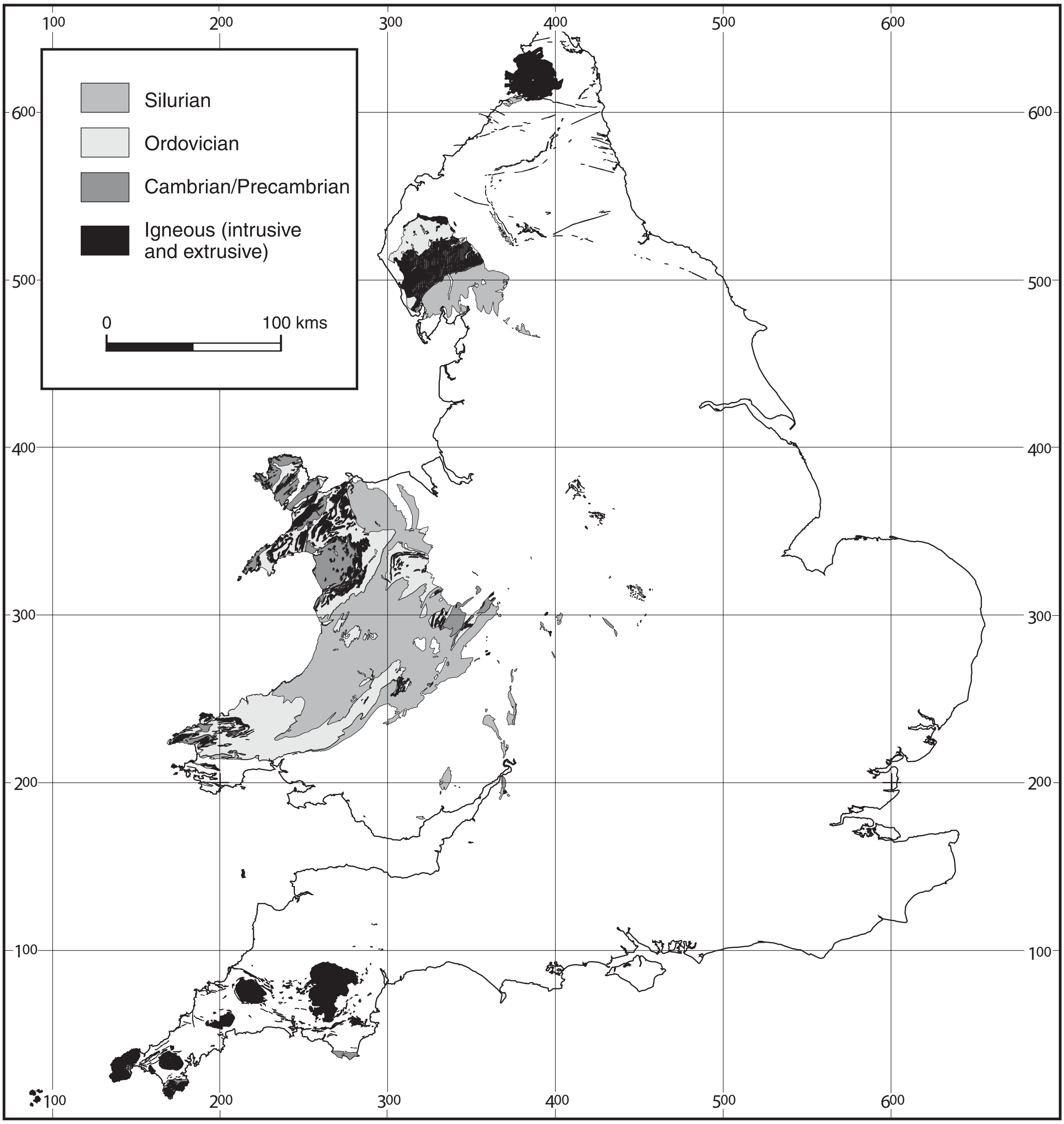

Figure 10.1 Distribution of Precambrian, Lower Palaeozoic and igneous rocks in England and Wales.

Group. Intense deformation and metamorphic alteration have affected all Malvernian rocks.

The Uriconian Volcanic Group of the Welsh Borderlands occurs along the Church Stretton Fault with individual sections up to 1200 m in thickness. The group comprises dominantly intermediate and acid lavas and pyroclastics with minor basic and acid intrusions. The rocks are much altered.

The Charnian rocks of the Charnwood Forest and Nuneaton areas of the East Midlands comprise a Precambrian sedimentary-volcanic group, at least 2600 m thick, cut by intrusive diorites. Pyroclastic and volcaniclastic tuffs, agglomerates and breccias occur in all but the upper 300 m of the succession and are associated with finely crystalline intermediate to acid lavas. The upper 300 m, the Brand Group, consists of an upward fining sequence ranging from coarse conglomerates to sands and silts, many of the larger grains being derived from volcanic rocks (Harris, 1992).

Grits, conglomerates and slates of the Comley Series predominate in the basal part of the Cambrian sequence of north Wales. The Comley Series is overlain by grits with mudstones, shales and siltstones of the Lingula Flags Group (Merioneth Series), the argillaceous strata becoming dominant in the upper part of the sequence. In south-west Wales the sequence generally consists of sandstones and shales of the Comley Group at the base (up to 350 m thick), overlain by the sandstones, shales and mudstones of the St David's Series (about 730 m thick). This is in turn overlain by over 600 m of micaceous flaggy shales alternating with sandy mudstones and sandstones of the Merioneth Series at the top of the sequence.

In Shropshire and Herefordshire, sandstones and quartzites dominate the lower Cambrian with shales dominant in the upper. In the Malverns, quartzites predominate. In the East Midlands, the lower part of the Cambrian sequence, the Hartshill Quartzite Formation (up to 150 m thick), is dominated by arenaceous rocks and is overlain by over 650 m of Stockingford Shales which are predominantly argillaceous although flags and grits also occur.

10.2.2.2 *Ordovician and Silurian*

The northern and western areas of the Welsh Basin are dominated by thick, relatively deep-water sediments including basinal mudstones and sandstone turbidites. The southern and eastern areas represented a stable shelf with relatively thin, shallow-water sedimentation. Volcanic rocks of Lower Palaeozoic age are also a major component of the Ordovician and Silurian strata, which constitute the upland areas of Snowdonia and the Lake District. The volcanicity for both areas was controlled by south-eastward directed subduction of oceanic lithosphere at the southern margin of the Iapetus Ocean. There is a broad thickening of strata westward toward the Welsh Basin.

In Wales, volcanic rocks are dominantly Ordovician in age, extending from late Tremadoc to Wenlock times. They occur in numerous volcanic centres and are marked by varied geochemistry. In the Snowdonia area, the activity was dominated by pyroclastic flow and ash fall deposits, which produced thousands of metres of mainly basaltic and rhyolitic rocks. The most complete succession is in north Wales, but other areas include Dyfed, Powys and the Welsh Borderland. Sills of dolerite are relatively common, some up to 140 m thick. More rarely, there are rhyolitic plugs with sills and dykes. During Arenig times, basal conglomeratic sandstones developed at the basin margin with marked thickness variations, e.g. 10 to 30 m in the Harlech Dome to about 1000 m in north Anglesey. These sandstones pass upwards into a mudstone-dominated succession.

Following the main phase of Ordovician activity, from the end of Ashgill to early Wenlock times, extrusive rocks developed on Skomer Island as a 1000 m thick succession of basaltic lavas interstratified with sedimentary rocks. Elsewhere at this time, an altered 18 m thick andesite was extruded in the Tortworth Inlier in Avon and at least 120 m of lava above 48 m of tuffs in the Mendips, Somerset.

In the Lake District, the Eycott Volcanic Group is Arenig to Llanvirn in age (Ordovician), comprising 2500 m of basalts, andesites and related tuffs that rest conformably upon, and are interleaved with, the Skiddaw Group. The latter is composed of a thick sequence of mudstones with siltstones and sandstones. The Borrowdale Volcanic Group ranges in age from Arenig to Ashgill (Ordovician), though maximum volcanicity occurred during Llandeilo and Caradocian times. They rest unconformably upon the Skiddaw Group. The Borrowdale Volcanic Group is in excess of 6000 m thick. The lowest of the volcanics are typically basaltic, followed by andesite, dacite and rhyolite lavas and related pyroclastic deposits, such as ash-fall tuffs and ignimbrites. These volcanic rocks typically display abrupt lateral variations in composition. A later minor volcanic event during Ashgill times produced the Stockdale Rhyolite, up to 150 m thick, and associated tuffs, up to 5 m thick.

The Silurian lithostratigraphical nomenclature has been extensively revised over recent years. In the West Midlands, the Wenlock Shales have been subdivided and are now known as the Buildwas and Coalbrookdale formations. The Buildwas Formation comprises olive-green and grey calcareous mudstone and nodular to lenticular limestone with shell fragments throughout. The Coalbrookdale Formation is composed of compact, well-bedded, olive-grey to dark blue-grey silty mudstones with some calcareous siltstones, nodular calcareous beds and bentonites. In the West Midlands, the Buildwas Formation is about 20 m thick and the Coalbrookdale Formation about 150 to 210 m, the two formations being separated by the c.10 m thick Barr Limestone. In the Welsh Borderlands, the equivalent formations (formerly the Wenlock Limestones and Wenlock Shales) are 25 to 40 m and 190 to 265 m thick, respectively and overlie the May Hill Sandstone of Llandovery age. A combined thickness of more than 650 m is is indicated to the southeast of Hereford

The Lower Ludlow Shales and Upper Ludlow Shales in the West Midlands are now known as the Elton and Whitcliffe formations respectively. The Elton Formation comprises green-grey shales, silty and sandy mudstones and siltstones, with thin beds of nodular limestone. The formation is shelly throughout. The Whitcliffe Formation is grey to greenish grey, flaggy, calcareous siltstone with shelly limestone beds in the Welsh Borderlands. In the West Midlands the formation comprises an upward transition from argillaceous flaggy limestone to olive-buff shaley mudstone overlain by buff silty sandstone and mudstone. In the West Midlands the Elton Formation is about 150 m thick and the Whitcliffe Formation about 10 to 15 m, the two formations being separated by the 8 m thick Aymestry Limestone. In the Welsh Borderlands, the equivalent formations are the 220 to 240 m and 55 m thick, respectively, separated by the up to 45 m thick Aymestry Limestone. South-east of Hereford in the Woolhope Inlier the equivalent Lower Ludlow Siltstone (up to 285 m thick) is separated from the Upper Ludlow Siltsone (up to 85 m) by the 15 m thick Aymestry Limestone.

10.2.2.3 *Relationships with older and younger strata*

Sedimentary rocks of Arenig (Ordovician) age overlap eastward onto the shelf area of the Welsh Borderlands over a folded and eroded surface of Tremadoc mudstones. Silurian strata rest unconformably upon Ordovician to Precambrian strata. The succession of Wenlock and Ludlow age is typically conformable throughout and passes upwards into red mudstones and sandstones of Přídolí and Devonian age. There is a thinning of strata eastwards away from the Welsh Basin. In the West Midlands the Coal Measures of Silesian age occur unconformably on Silurian strata.

10.2.2.4 *Cementation*

Pre-Devonian rocks are, almost without exception very well cemented and consolidated. Silurian strata in the Welsh Borderlands and West Midlands are dominated by calcite cementation, notably with the formation of nodular and lensoid limestones.

10.2.2.5 *Structural geology*

The main structural elements affecting pre-Devonian and igneous rocks in England and Wales are shown in Figure 10.2. Lower Palaeozoic rocks have been subjected to Caledonian, Hercynian and Mesozoic deformation in varying degrees, depending on location. The older formations have also undergone at least one Precambrian orogenic deformation episode.

Precambrian deformation

Evidence of the nature of Precambrian deformation essentially is derived from the metamorphic gneisses at the base of the Monian Supergroup of north Wales and present in the

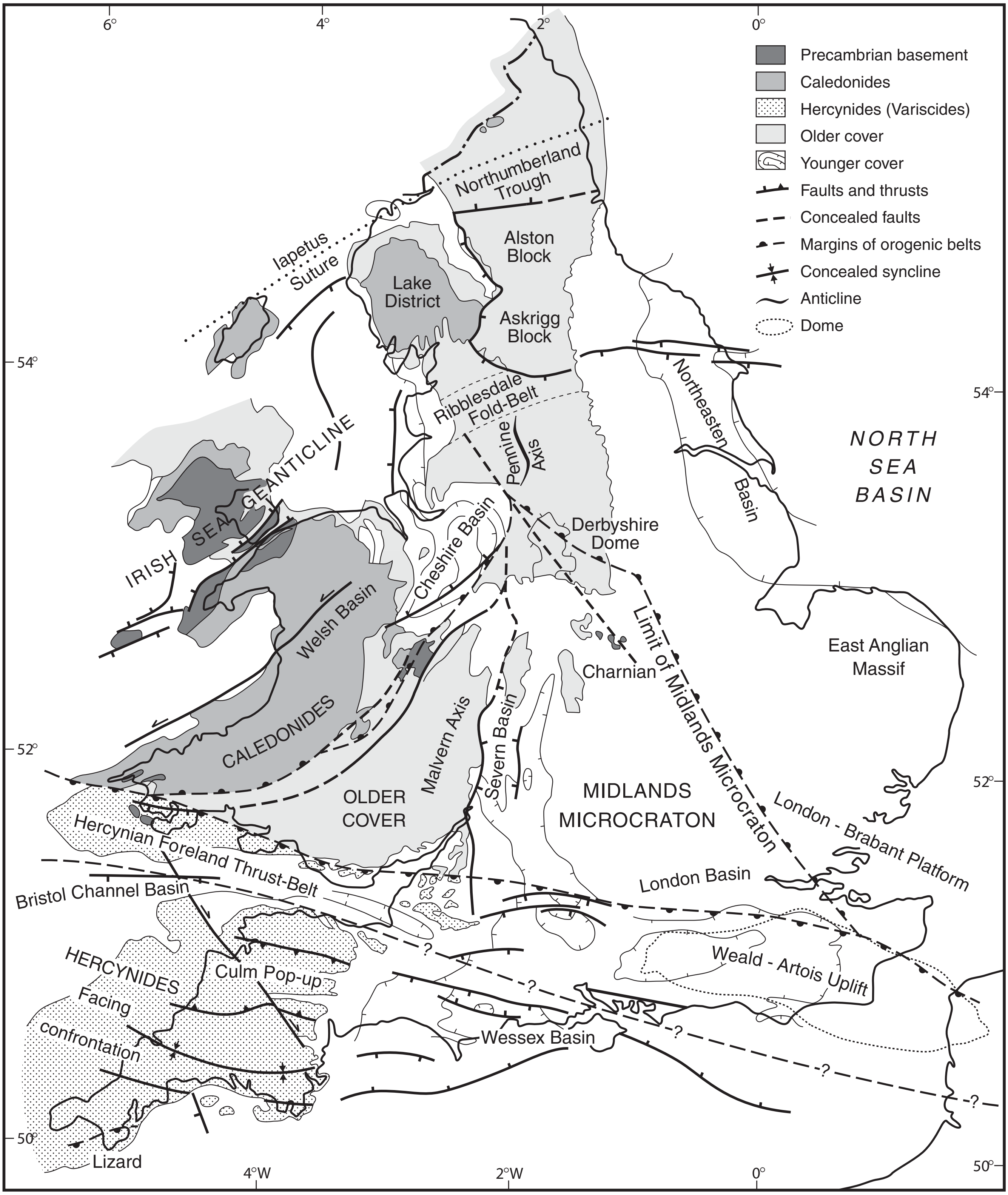

Figure 10.2 Main structural elements affecting pre-Devonian and igneous rocks in England and Wales.

Malvernian of the Welsh Borders. In these areas, interpretation is complicated by the dominance of Caledonian structures, often making it difficult to identify Precambrian structures. However, foliation within Malvernian rocks is considered to be late Precambrian in age. This deformation produced the prominent north–south basement lineaments present in the Midlands Microcraton which reflect the suture between two terranes. The mainly non-metamorphic Uriconian-Longmyndian rocks of the Midlands Microcraton are typically strongly folded, although this folding is likely to be associated with later displacements along major basement lineaments which brought Precambrian strata to their current structural position.

Although structures associated with the late Proterozoic (Cadomian) orogeny are difficult to identify, the universal identification of an unconformity between Lower Palaeozoic and Precambrian strata suggests that this orogeny affected the entire basement of England and Wales.

Caledonian deformation

Caledonian structures in England and Wales can be subdivided into those of typical Caledonian north-east trend, particularly evident in Wales and northern England and north-west trending Charnian structures, evident in the East Midlands. The latter may represent reactivations of pre-existing Precambrian lineaments.

The Caledonian structures parallel the orientation of the Iapetus Suture and were largely produced by late Silurian to Early Devonian collision of plates that formed this suture. In the Lake District, the principal structures are lithology dependent with the Skiddaw Slates displaying east-north-east trending upright folds and a slightly incongruous cleavage, in turn locally deformed by a sub-horizontal crenulation or fracture cleavage and associated recumbent folds. The Borrowdale Volcanic Group is folded into major open buckles.

Silurian rocks are variably deformed into open concentric folds in arenaceous strata and tight folds in argillaceous strata. The cleavage in the Silurian strata is slightly incongruous to the folding and decreases towards the south. In Wales, the Lower Palaeozoic strata are typically strongly folded, overthrust with a dominant south-east trend and associated with a slatey cleavage and zeolite facies metamorphism. In the southern part of the Welsh Basin, the folding is simple and of typical north-east trend. In the northern part of the basin this structure is complicated by the presence of domes, depressions, major faults and complex cleavage patterns. There is a dramatic decrease in the intensity of folding and cleavage towards the south-east such that, in the Welsh Borders, Silurian and Lower Devonian strata lack a slatey cleavage and are only very gently folded parallel with the north-east trending major basement lineaments, e.g. the Pontesford-Linley and Church Stretton fault systems. These faults, which mark the boundary between the Welsh Basin and Midlands Microcraton, have been interpreted as having large components of strike-slip displacement.

Hercynian deformation

During Late Devonian and Dinantian times a phase of north-south extension resulted in the development of graben and half-graben which controlled sedimentation in the central and northern parts of England. Among the features generated were stable platform blocks such as the Askrigg and Alston blocks and the Derbyshire Dome and Wales-Brabant High which underwent relatively little subsidence and at times may have been emergent and subject to erosion. The platforms were separated by basins, (such as the Northumberland and Stainmore troughs, the Craven Basin and Edale and Widmerpool gulfs), associated with rapid subsidence. The geometry of the basins and platforms was largely controlled by pre-existing crustal structures. During Namurian and Westphalian times there was a transition to a period in which subsidence dominated, producing the Pennine Basin north of the Wales-Brabant High in the former area of greatest lithospheric extension. Pulses of relatively minor compression, inversion of faults, formation of unconformities and growth folding become increasingly prevalent from Bolsovian (Westphalian C) to Early Permian times culminating in the end Carboniferous to Early Permian uplift and erosion associated with the Sub-Permian Unconformity. Reactivation of basement lineaments produced reverse faults or oblique wrench faults depending upon the orientation of the structures relative to the axis of compression. Major structures such as the South Wales Syncline and possibly the Pennine Anticline were produced by this event.

South of the Wales-Brabant High, compressional deformation associated with the Variscan event may have been initiated as early as Late Devonian and continued through to the end-Carboniferous, with a broad northward migration of deformation with time. Simplistically, the deformation has been interpreted as shallow thrust-folding generated by north–south compression. In south Wales the northern part of the coalfield shows relatively small disturbances of Caledonian trend, whereas in the south of the coalfield and also in the Mendips there is intense folding and thrusting with vergence of folds towards the north. In north Devon there is an east–west trending anticline with divergent-facing folds thought to be Silesian in age. In central Cornwall and south Devon the folding is north facing with the recumbent folds having a slatey cleavage that dies out northwards and is thought to be Dinantian in age. In south Cornwall the thrusts and folds have a north-easterly verge and are thought to have a Late Devonian age. The most southerly outcropping nappe comprises the Lizard Complex.

Mesozoic deformation

North of a line between the Severn and Thames estuaries sedimentary rocks are broadly flexed, domed, tilted and fractured by movements which may have started during the Permo-Triassic and continued to mid- or end-Cretaceous age, which are possibly associated with east–west extension during the opening of the North Atlantic. The principal feature of the Mesozoic deformation is the reactivation of basement lineaments of the three principal trends: the north-east trending Caledonian lineaments, the north trending Malvernian lineaments and the north-west trending Charnian lineaments.

Jointing

Relatively little information is available on the subject of joints. In a detailed study in northern England, it was determined that joint sets tended to parallel the grain of the principal basement structures, i.e. north-west, north and north-east trending. Although the study was carried out principally on joints in Carboniferous strata it was identified that the joints in older and younger strata were parallel to the Carboniferous joints. It is possible that the stress fields associated with the development of joints are controlled by the orientation of basement lineaments and have persisted over long periods of geological time.

10.2.3 Hydrogeology

10.2.3.1 *Introduction*

The principal controls on the core and aquifer properties of the pre-Devonian aquifers are the degree of induration and cementation as well as the extent and depth of fracturing. Primary porosity in most horizons is very low (commonly less than 2%). Flow is almost entirely via fractures, and groundwater flow and storage occurs in joints and fracture systems developed to varying degrees according to the formation's deformation history and proximity to local structural features such as faults and fold axes. Primary porosity therefore contributes an insignificant proportion of the total permeability and storage. Below the weathered zone, aquifer properties appear to be less dependent on lithology than is the case with both Devonian and Carboniferous rocks. The possible exceptions are the Silurian limestones where there is potential for the enlargement of fractures by solution.

Spring locations are often closely associated with major lineaments and faults. For example, springs occur at the margin of the Llandrindod Wells Inlier (Ordovician) which lies along the north-east–south-west trending Pontesford Lineament and which is extensively fractured by north-east–south-west and east–west trending faults (Merrin, 1996). Springs located at Builth Wells, Llangammarch Wells, Llanwrtyd Wells and Wenton issue from Silurian and Ordovician strata along north-east–south-west trending structures and faults paralleling the Pontesford Lineament in the same area (Edmunds et al., 1998). In the Shucknall and Woolhope area south-east of Hereford, Silurian Wenlock and Ludlow strata are up-faulted against the overlying Old Red Sandstone along the Vale of Neath Disturbance. Springs issuing from the Wenlock beds along the fault, at the juxtaposition with the (relatively impermeable) Old Red Sandstone strata, have historically represented the main water supply to nearby villages (D Headworth, Environment Agency, personal communication, 4 Jan 2000).

10.2.3.2 *Previous studies*

Few hydrogeological studies have been carried out specifically on pre-Devonian rocks. Those that do exist are predominantly hydrogeochemical in nature and include relatively little information regarding aquifer properties.

The geochemistry and origins of spring waters at Llandrindod and Builth Wells have been investigated in considerable detail (Merrin, 1996; Edmunds et al., 1998). A detailed hydrological and hydrogeological study of the Plynlimon catchment in central Wales, an area underlain by Ordovician and Silurian mudstones provides a detailed assessment of groundwater chemistry and also some information from pumping tests and flow logging carried out on three boreholes (Neal et al., 1997).

Investigations have also been carried out in the Afon Teifi valley in west Wales. The study was primarily concerned with groundwater resources in the superficial sands and gravels, but also provided information on Silurian and Ordovician shale and greywacke bedrock (Robins et al., in press).

Extensive investigations and groundwater modeling have been carried out in the Sellafield area on the western fringes of the Lake District. Most attention centred on the aquifer characteristics of the superficial deposits and Triassic sandstones but a very limited amount of information on deep underlying Ordovician Borrowdale Volcanic Group present at considerable depth was published (Heathcote et al., 1996).

Fragmentary information on yields and quality of pre-Devonian groundwaters is contained in several geological memoirs for various parts of Wales but the only significant entry is provided by Greig et al. (1968) for Geological Sheet 166 which covers the area around Church Stretton, Craven Arms, Wenlock Edge and Brown Clee. A limited amount of information for pre-Devonian rocks is available on the hydrogeological map for south Wales (British Geological Survey, 1986).

10.2.3.3 *Aquifer properties*

Aquifer testing was carried out in three boreholes that penetrated Silurian and Ordovician shale and greywacke bedrock in the Afon Teifi valley in west Wales. These tests provided transmissivities of 0.3 to 1.1 m^2/d (averaging about 0.6 m^2/d), compared to values of up to 210 m^2/d from nearby Quaternary gravels (Robins et al., in press).

In the Plynlimon catchment, in central Wales, flow logging and pumping was carried out in deep boreholes penetrating steeply dipping Ordovician and Silurian mudstones. Specific capacities of about 11, 20 and 663 $m^3/d/m$ were obtained from below 30 m depth. Unstressed temperature logs indicated a local base of groundwater circulation at 32 to 33 m below ground level and that groundwater temperatures were distinctly cooler above 10 m depth. It was concluded that shallow groundwater circulation and storage within the bedrock were probably an important factor in the catchment (Neal et al., 1997).

Edmunds et al. (1998) suggested that the intergranular permeabilities of the shales, mudstones and volcanic rocks of the Builth Inlier, in central Wales, were likely to be very low, (of the order of 10^{-3} m/d). Secondary permeability due to fracturing and faulting could however locally enhance the hydraulic conductivity at relatively shallow depths to as much as 10^{-1} m/d. It was concluded that much of the recharging water would discharge locally via short, shallow flow paths probably of only a few hundred metres. Residence times were likely to be short, of the order of months to a few years. Less commonly, deeper slower flow paths, permitting extended water-rock interactions along deeply penetrating fractures, may exist in the area.

Step and constant rate aquifer testing of a borehole penetrating Silurian Aberystwyth Grits Group, at a location near Bethania in central Wales, produced transmissivities ranging from 7 to 15 m^2/d, the lower value being considered representative of the aquifer as a whole in this area (N S Robins, personal communication). Pumping rates during step testing were between 108 and 338 m^3/d and the constant rate test was carried out at a discharge rate of 235 m^3/h. A storage coefficient of about 4×10^{-4}, derived from observation borehole water level measurements, was indicative of confined conditions, in keeping with the presence of a confining layer of boulder clay at the site.

10.2.3.4 *Core data*

Physical properties data derived from laboratory analysis are available for Precambrian core obtained from only four boreholes. Four samples obtained from depths between 90 and 100 m below ground level from Long Mynd Borehole [SO 4206 9533] provided porosity values ranging from 2.6 to 6.6% (average 4.1%). No permeability values are available.

Thirteen Precambrian core samples obtained from depths between 784 and 834 m below ground level, from Morley Quarry Borehole [SK 4765 1787] gave very low porosity and low permeability values, ranging from 0.175 to 1.4% (average 0.6%) and 0.02 to 0.83 m/d (average 0.11 m/d) respectively. A single sample obtained from a depth of 296 m below ground level at Wittering [TL 0492 0185] gave a porosity of about 2% and permeability of 0.005 m/d. Two samples from depths of 39 and 44 m below ground level in Kinley Farm Borehole [SJ 6716 1478] gave higher porosity values of 7 to 12% but again low permeabilities of 0.005 to 018 m/d.

No porosity or permeability data have been identified for Cambrian, Ordovician or Silurian rocks. It seems likely that values for these strata may be akin to those measured for Precambrian rocks in view of their similar dense, highly indurated and cemented nature.

10.2.3.5 *Pumping test results*

Data availability

Only very limited pumping test results providing transmissivity and specific capacity values are available in the Aquifer Properties Database. To supplement this data-poor area, the National Well Record Archive was examined to obtain additional yield and (where available) water level drawdown data for areas of Wales underlain by Ordovician and Cambrian rocks.

This exercise initially produced quite extensive listings, with yields for 38 Cambrian and 233 Ordovician sources and specific capacities for two and 102 locations respectively. A closer examination of this initial data set indicated however that in many cases the bedrock at the well site was overlain by permeable superficial deposits, (predominantly sands and gravels), which were undoubtedly contributing most, if not all, of the total yield. Removal of these multi-aquifer supplies left only two Cambrian and 16 Ordovician sources of which there were drawdowns for only one and seven sites respectively. Twenty three Cambrian and 69 Ordovician spring yields were also included in the original data set. Yields from both data sets are discussed in more detail below.

Transmissivity and specific capacity

Specific capacities from the archive data for the seven Ordovician boreholes and wells range from 0.3 to over 20 000 m^3/d/m. The geometric mean of 22.9 m^3/d/m indicates however that the maximum value is distinctly anomalous and that representative values are likely to be at the lower end of the range. The sole specific capacity for a Cambrian site is 11.9 m^3/d/m.

Pumping test results from the aquifer properties database are available for only 12 sites underlain by pre-Devonian rocks. Of these 11 sites are Silurian, one is Ordovician and there are no results for the Cambrian or Precambrian rocks. Pumping rates range from about 30 m^3/d to over 800 m^3/d, with a single very high rate of over 2300 m^3/d. Some of these rates are far higher than the yields normally expected from these strata suggesting either abnormal site conditions or possibly some contribution to the total yield from overlying highly permeable superficial deposits.

Table 10.2 summarises the results for the 12 sites. Their extreme variability is reflected in the wide interquartile ranges of the aquifer properties. The specific capacity values range from 0.8 to 570 m^3/d/m but few exceed 100 m^3/d/m. The geometric mean is 24.8 m^3/d/m, very similar to that obtained from the archive data for Ordovician strata. Transmissivity values range from 0.7 to 98 m^2/d, with one exceptional value of over 3900 m^2/d. It is considered probable that the available data largely originates from sites where anomalous aquifer conditions exist and which in consequence produced yields that were sufficiently high to justify pump testing.

Only a single storage coefficient value is available (0.02) indicating unconfined conditions.

10.2.3.6 *Yield data*

Yields of up to 43 m^3/d (0.5 l/s) have been obtained from shallow wells and springs in the fissured Wenlock and Aymestry limestones (Silurian) of south Wales. Ordovician rocks were not however considered to form a usable aquifer, with yields generally of less than 8.6 m^3/d. Cambrian and Precambrian rocks in south Wales were of low permeability and at best yielded small amounts of groundwater from springs and shallow boreholes penetrating fractured or weathered rocks (British Geological Survey, 1986).

In the Welsh Borders, around Church Stretton, Craven Arms, Wenlock Edge and Brown Clee, yields from nine boreholes drilled into the Precambrian ranged from dry to 65.5 m^3/d with one exceptional borehole at Aston on Clun recording over 260 m^3/d (Greig et al., 1968). No boreholes penetrating Cambrian rocks were recorded in the area. Yields from the Ordovician rocks were reported to range from nil to about 220 m^3/d and boreholes could generally be expected to provide less than 22 m^3/d. Yields from Llandovery and Wenlock (Silurian) boreholes commonly provided up to 35 m^3/d, the largest recorded being almost 120 m^3/d. Saline waters have however been encountered in the Llandovery strata. Yields from the Elton and Whitcliffe formations ranged from nil to 109 m^3/d, with one exceptional yield of 545 m^3/d from a borehole mainly penetrating the Whitcliffe Formation (Upper Ludlow) at Diddlebury [SO 505 856]. It was also noted that many springs issued from the base of the Aymestry Limestone and to a lesser extent the Wenlock Limestone (Greig et al., 1968). In the Worcester area, the few wells and boreholes penetrating the Silurian strata generally provided yields of less than 43 m^3/d (Barclay et al., 1997).

While other geological sheet memoirs do not cite quantitative information on yields from Lower Palaeozoic strata, there are frequent references to the dependence of the rural community on shallow wells and small springs issuing from these rocks (e.g. Warren et al., 1984; Wedd et al., 1928; 1929; Strahan et al., 1909; Barclay, 1989).

Yields for 17 wells and boreholes penetrating Cambrian and Ordovician strata (obtained from the National Water Well Archive) are summarised in Table 10.3, and for springs issuing from the same strata in Table 10.4.

Yields recorded for all of the source types are uniformly low with the maximum yield (from a spring) of only 63 m^3/d.

Table 10.2 Summary of aquifer properties results for pre-Devonian aquifers in England and Wales.

Pre-Devonian aquifers		
Total number of records	13	—
Number of transmissivity records	8	—
Minimum/maximum transmissivity value (m^2/d)	0.71	3902
Arithmetic/geometric mean of transmissivity (m^2/d)	548	26.2
Median/interquartile range of transmissivity (m^2/d)	18.7	248
25/75 percentile of transmissivity (m^2/d)	2.51	150
Number of storage coefficient values	2	—
Minimum/maximum storage coefficient value	0.0035	0.02
Number of specific capacity values (m^3/d/m)	10	—
Minimum/maximum specific capacity value (m^3/d/m)	0.81	571
Arithmetic/geometric mean of specific capacity values (m^3/d/m)	101	24.8
Median/interquartile range of specific capacity values (m^3/d/m)	39.7	100
25/75 percentile of specific capacity values (m^3/d/m)	4.8	105

Table 10.3 Summary of borehole and well yields for the Cambrian and Ordovician of Wales and the Welsh Borders.

	Cambrian		Ordovician	
Total number of records	2	—	16	—
Number of yield values	2	—	15	—
Minimum/maximum yield value (m^3/d)	0.4	1.26	0.03	17.0
Arithmetic/geometric mean of yield (m^3/d)	0.8	0.7	3.06	0.46
Median/interquartile range of yield (m^3/d)	—	—	0.27	3.27
25/75 percentile of yield (m^3/d)	—	—	0.06	3.33

Table 10.4 Summary of spring yields for the Cambrian and Ordovician of Wales and the Welsh Borders.

	Cambrian		Ordovician	
Total number of records	23	—	69	—
Number of yield values	23	—	69	—
Minimum/maximum yield value (m^3/d)	0.08	63.14	0.01	7.89
Arithmetic/geometric mean of yield (m^3/d)	7.62	3.79	0.86	0.30
Median/interquartile range of yield (m^3/d)	2.63	6.84	0.35	0.62
25/75 percentile of yield (m^3/d)	2.63	9.47	0.14	0.76

As noted in Section 10.1, there is an inherent bias in the data towards low values. It is probable that springs that had a higher, more sustainable yield would be more likely to be used for private domestic supplies and therefore to be recorded on the BGS archive. Many spring yields would be of a similar capacity to those found that at the lower end of the range (or lower) and many would be expected to dry up during lengthy periods without rainfall.

10.2.3.7 *Controls on permeability and transmissivity*

The principal controls on permeability and transmissivity of the pre-Devonian aquifers are the degree of induration and cementation, and the extent and depth of fracturing. The polyphase deformation some of these strata have undergone means that fractures arise from a number of different structural causes; folding, faulting, jointing, imparting of cleavage. For example, intense folding, deformation and low grade metamorphism has, in many areas, stimulated the development of axial plane cleavage systems. Where such cleavage patterns intersect fractures and joints, there are opportunities for groundwater flow along interconnected fracture systems. As previously discussed for the Devonian rocks (9.3.2.5), fracture systems may occur in tight folds, due to the development of radial joints around the crests of anticlines and rotation joints along the limbs; as these fractures are tensional they may remain open (Figure 9.15 (after Price, 1966)).

Weathering of pre-Devonian rocks at outcrop is highly variable, often being several metres thick in valleys but thin or absent in upland locations. The degree of fracturing is commonly enhanced by the weathering process, which increases the permeability of the upper part of the aquifer. The effects of burial and subsequent rebound during the periods of glaciation are also believed to have exerted both regional and localised effects on permeability development (D Headworth, Environment Agency, personal communication, 4 Jan 2000).

The occurrence of open, water-bearing fractures is also greatest at shallower depths with permeability declining rapidly with depth, as fractures become tighter and less common. This marked reduction in permeability with depth effectively imposes a base to the aquifer which drilling experience has shown for practical purposes to be commonly around 30 to 40 m. At higher elevations, fractures capable of bearing water are likely to be present although the depth of weathering may be minimal. Although such fracture systems are commonly dry, or may only constitute transitory perched aquifers due to rapid drainage, they can act as conduits for recharge to aquifer horizons at lower elevations.

Quantitatively, the effect of such controls remains speculative, and this study has not identified any field or site-specific studies in England and Wales that illustrate their possible magnitude.

10.3 IGNEOUS INTRUSIVE ROCKS

10.3.1 Introduction

The main outcrops of intrusive igneous rocks are located in the south-west of England, in the Lake District and the Cheviots of northern England (Figure 10.1). While there are also numerous small intrusive rock outcrops of various ages in Anglesey, north-west, central and south-west Wales, the Midlands, Peak District and other parts of the Pennines in England, few physical properties data are available. Apart from a brief geological description to put them in context, they are not discussed further.

Of the igneous intrusions discussed below, significant information regarding hydrogeological characteristics is only available for the granites of south-west England. There are also very limited data for the Lizard Complex of Cornwall and the diorites of south Leicestershire. The geological nature of these igneous intrusions is therefore discussed in more detail, as are their hydrogeological characteristics in the following sections.

10.3.2 Intrusion ages and lithological variations

10.3.2.1 *General*

Caledonian granites and diorites occur in a northern group intruded into the north-east to south-west trending Caledonides of northern England. Intrusions in north Wales, including granophyres and dolerites, are minor and associated with Ordovician volcanicity.

The Cheviot intrusive body, which outcrops over an area of 52 km^2, has affinities with granites in the Southern Uplands. The igneous activity commenced during the Early Devonian with a volcanic phase emitting pyroclastics and rhyolites, followed by a 500 m thickness of andesites and pyroclastics in turn overlain by 1000 m of lavas. The volcanic rocks were soon intruded by a complex of granite, diorite to granodiorite and granophyre. The intrusion produced a contact-metamorphic aureole about 2 km wide. The complex includes numerous north-north-west to south-south-east and north-north-east to south-south-west trending microgranite, granophyre and porphyry dykes that intruded the thick lava pile.

The Lake District is considered to be underlain by a large composite batholith that locally occurs at outcrop. The earliest intrusion is that of the Carrock Fell complex, which includes steeply dipping Ordovician gabbros intruded by granophyre. Further intrusions include those of the Eskdale Granite, the Ennerdale Granophyre, with the final intrusions during Early Devonian times including the Shap and Skiddaw granites, the latter with a prominent contact-metamorphic aureole.

There are pre-Carboniferous buried granites recognised in the north Pennines, with the Weardale and Wensleydale granites intruded into the basement of the Alston and Askrigg blocks respectively.

The intrusive complexes of the English Midlands are largely buried beneath Triassic rocks but appear to form a west-north-west to east-south-east belt emplaced into Lower Palaeozoic sedimentary rocks. They are of Ordovician age and include the South Leicestershire Tonalite, the Mountsorrel Granodiorite and Dosthill Dioritic Sill.

The emplacement of the calc-alkaline granite batholith of south-west England occurred during late Carboniferous to Early Permian times, following the final compressional phase of the Variscan orogeny.

In northern England, a tholeiitic intrusive phase is evident as a transgressive quartz-dolerite sill complex, the Whin Sill, which intrudes dominantly Lower Carboniferous sedimentary rocks of the Alston Block and Northumberland Trough and is considered to be end-Carboniferous to Permian in age. The sill has a maximum thickness in Teesdale of 73 m, thinning, splitting and rising in stratigraphical level eastwards. The sill is more coarsely crystalline away from the sill margins, which are often white due to alteration of feldspars to clay minerals and ferromagnesian minerals to carbonates. Associated with the Whin Sill are east-north-east to west-south-west trending dykes that are up to 10 m in thickness. Neither the sill nor dykes have been found to intrude Permian strata.

10.3.2.2 *The granites of south-west England*

There are six major outcrops of granite in south-west England (Figure 10.3), which from east to west are the Dartmoor (600 km^2 area), Bodmin Moor (190 km^2), St. Austell (85 km^2), Carnmenellis (130 km^2) with Tregonning-Godolphin, Land's End (190 km^2) and Scilly Isles. These are considered to be part of the Cornubian Batholith.

The granite masses or bosses are offshoots from the batholith and typically have a circular or sub-circular outcrop. Geophysical evidence suggests that they approximate to a cylindrical structure below surface. The contacts with country-rock are always sharp and often transgressive. Sheets and dykes often vein the country-rock. Deformation of the country-rock around the large bodies suggests forceful emplacement, whereas smaller intrusions appear to have passively intruded the host rock without significant deformation. A contact-metamorphic aureole is well developed around the granite masses, increasing in metamorphic grade to hornblende-hornfels facies in the zone nearest to the granite. Extensive metasomatism is present in the aureole of the Land's End Granite.

Biotite granite comprises over 90% of the exposed batholith, the rest being made up of lithium-mica granite and fluorite granite. Biotite granite is commonly composed of quartz, potassium feldspar, plagioclase feldspar, biotite, muscovite (usually secondary) and tourmaline, which occurs as an accessory mineral. Potassium feldspar megacrysts can reach nearly 20 cm in length but they are usually in the range of 1.5 to 5 cm. Fine-grained biotite granite, with or without megacrysts of potassium feldspar, occurs as flat lying sheets in all the granite masses. Lithium-mica granite forms much of the western part of the St Austell Granite and Tregonning Granite. Late-stage intrusions of microgranite and aplite in veins and dykes are common in all the granite masses. A magmatically related but slightly younger intrusion of east-north-east to west-south-west trending quartz-porphyry dykes cut all the bosses with the exception of the Land's End Granite.

Late-stage hydrothermal alteration of the granites by boron- and fluorine-rich fluids gave rise to tourmalinisation and greisenisation, respectively. These processes usually result in the formation of veins but may also pervade the granite more diffusely. Tourmalinisation forms quartz-tourmaline veins commonly accompanied by haematite and greisenisation forms veins characterized by quartz, white mica, topaz and fluorite. As the granites cooled, low-temperature hydrothermal fluids circulated and began altering feldspars to kaolin, a process that may have continued subsequently over millions of years under suitable weathering conditions.

As the granite magma consolidated, water began to circulate in convectional systems within the joints, driven by the heat of the cooling batholith. Metals were scavenged from both the granite and the country rocks through which the fluids passed, and deposited as minerals on the walls of fractures in the cooler, upper part of the convectional cycle. The association of copper and tin with south-west England is well known but ores of arsenic, antimony, barium, bismuth, iron, lead, manganese, silver, uranium, wolfram and zinc have also been worked.

Joints are lines of weakness or microfractures that formed in the granite in response to stresses operating at the time the granite magma consolidated. The principal joints in the main granite masses trend north-north-west to south-south-east, which is also the same as the common alignment of feldspar megacrysts. Another prominent joint set trends east-north-east to west-south-west, parallel to the trend of the mineral lodes and the quartz porphyry dykes. Four main joint trends, (north–south, north-north-west to south-south-east, north-north-east to south-south-west, and east-south-east to west-north-west), have been recognised in the St Austell Granite (Exley, 1959). In the Carnmenellis Granite, four main joint trends were recognised (British Geological Survey, 1989):

- vertical joints trending 340°
- inclined joints trending 242°, dipping 70–80°N
- vertical joints trending 012°
- vertical east–west trending joints.

Flat lying joints are common near the surface. These are the results of stress relief and can be seen to mimic the topography in some areas. In quarries the frequency of this type of joint increases markedly from the floor to the top of a vertical face.

10.3.2.3 *Lizard Complex*

The complex forms the major part of the Lizard Peninsula of southern Cornwall (Figure 10.3) and is a Devonian

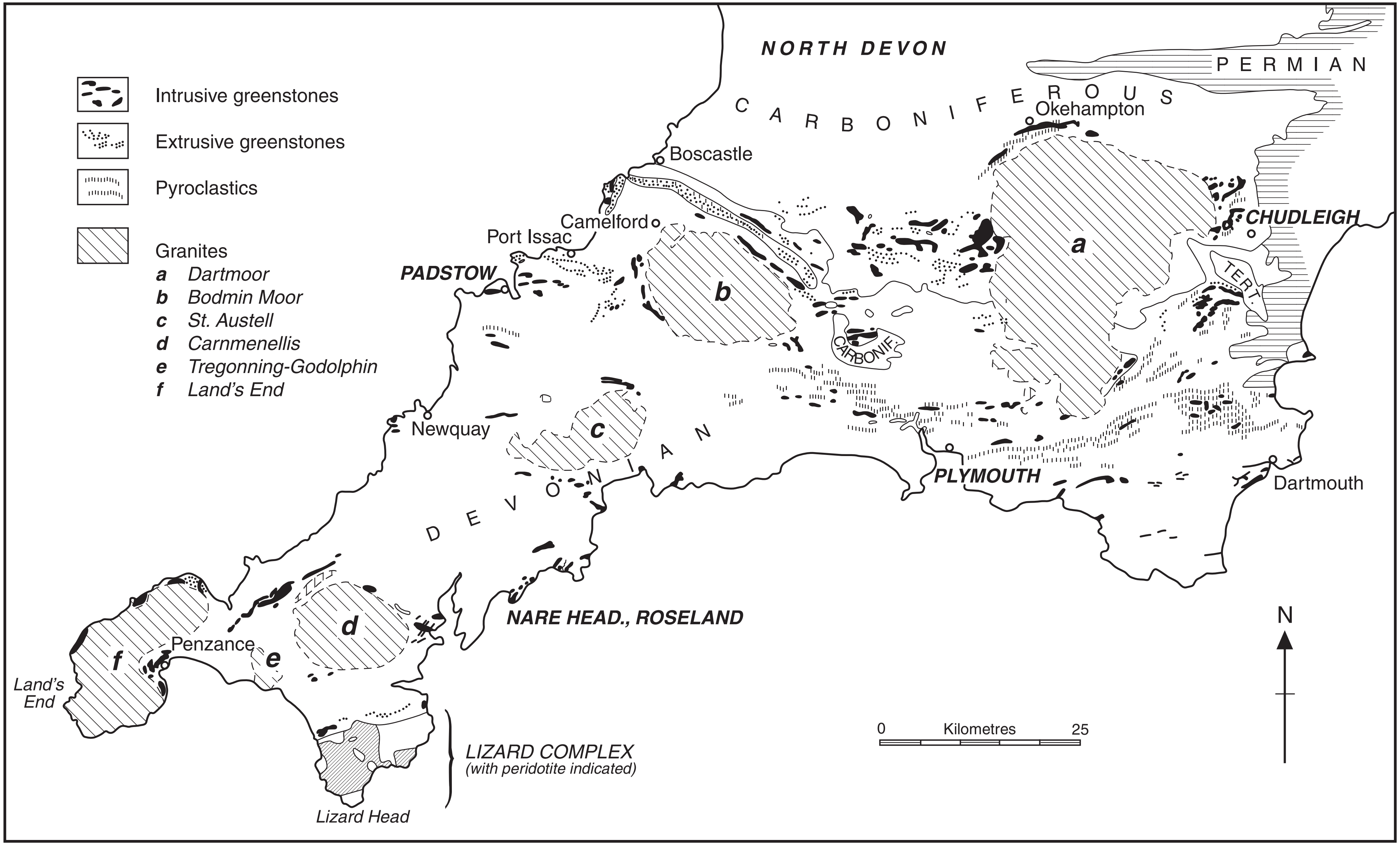

Figure 10.3 Distribution of granite outcrops in south-west England (after Floyd et al., 1993).

ophiolite, obducted during the Variscan orogeny. It is in downfaulted contact with Upper Devonian Meneage Breccias to the north, and rests in thrust contact with mica and amphibolite schists, of probable Early Devonian age, at Old Lizard Head to the south. The Man of War Gneiss in offshore reefs south of Lizard Point probably represents overthrust continental basement.

The maximum thickness of the thrust sheet is probably not much more than the 360 m recorded in Floyd et al. (1993), but the complex includes elements derived from different levels of ocean crust and underlying mantle.

The ophiolite is a tectonically complex association of mantle peridotites, variously serpentinised, metamorphosed cumulates, intrusive gabbroic rocks, sheeted dykes and intrusive acid gneisses.

The Landewednack and Traboe hornblende-schists are amphibolite-facies regionally metamorphosed basic igneous rocks. The Landewednack Schists, largely located around the southern tip of the Lizard, were essentially basaltic lavas metamorphosed during obduction. The Traboe Schists, in the Traboe, Mullion and Predannack areas, are largely cumulates within the ophiolite, metamorphosed at high temperatures within the crust prior to obduction.

10.3.2.4 *South Leicestershire diorites*

The diorites are limited to four small inliers east of Hinkley in south Leicestershire. The intrusion is considered to be of Ordovician age. Although intrusive contacts are not seen the diorites probably intrude strata of Cambrian (Stockingford Shale Group) age. The four individual outcrops are linked at depth to form a single pluton. Exhumation due to erosion produced an ancient landscape in which the diorites produced small ridges which were subsequently buried by rocks of the Triassic Mercia Mudstone Group. The intrusions are mainly quartz-diorites with quartz, plagioclase and subordinate alkali feldspar and hornblende. The diorites are transected by east–west and north-east–south-west trending joint sets. The former dip between 50 and 60° to the south. Plagioclase tends to be extensively altered to white mica and hornblende to chlorite.

10.3.3 Hydrogeology

10.3.3.1 *Introduction*

The granites of south-west England, (and intrusives elsewhere in England and Wales), are characterised by fracture permeability with groundwater storage and flow occurring entirely within discrete fractures separated by a rock matrix of negligible permeability. There is a marked reduction in permeability with depth due to fractures becoming tighter and less common. This effectively imposes a base to the aquifer, commonly quoted as occurring at 30 to 40 m below ground level.

Groundwater from igneous intrusive rocks does not appear to be widely used, although undoubtedly yields capable of meeting small domestic requirements can be secured.

10.3.3.2 *Previous studies*

Review of the literature showed only one major hydrogeological study carried out on British igneous rocks, which was as research into the geothermal potential of the Carnmenellis Granite in Cornwall. Publications resulting from this work are predominantly concerned with hydrogeochemistry but the works of Edmunds et al. (1989) and Smedley et al. (1989) contain limited amounts of information on physical properties.

Other Carnmenellis Granite borehole investigations were also carried out at Carwynnen Quarry, during which hydraulic conductivities were determined by the use of packer testing (Heath and Durrance, 1985). Results obtained from this work are set out below.

There is little other published material of hydrogeological interest on the igneous aquifers of England and Wales. Commentary is found in the water supply contributions in some of the BGS memoirs for geological maps that contain igneous outcrops, although the older memoirs tend to be qualitative or superficial.

10.3.3.3 *Core data*

Hydraulic conductivities as low as 10^{-10} m/d have been reported for granites in the south-west (Batchelor, 1978). Hydraulic testing provided values many orders of magnitude higher (10^{-3} to 10^{-3} m/d), leading Heath and Durrance (1985) to conclude that the hydraulic properties of the rock mass are profoundly affected by the presence of a small number of major hydraulic features.

Little core data were available from the core properties database, results being limited to three boreholes drilled in the Carnmenellis Granite. Two of the boreholes were drilled at Rosemanowes Quarry [SW 7354 3562] as part of research into the geothermal potential of the area. Three samples were analysed, two from unknown depths from one borehole and a single sample from a depth of 1780 m below ground level in the other borehole. Porosity values were low (0.25 to 1.2%). Eleven samples were obtained from the other borehole, at an un-named location, between depths of 12.9 and 194 m below ground level. The shallowest sample had a porosity of almost 17%, with values for depths between 20 and 30 m of 2.4 and 3.7% and from depths exceeding 95 m of 0.5 to 2%. The latter are surprisingly high for granite at these depths. This variation of porosity with depth is almost certainly a reflection of a rapid transition from highly weathered granite near surface to fresh granites at depth. No core permeability data are available.

10.3.3.4 *Packer test results*

Heath and Durrance (1985) provided details of packer testing which was carried out on four boreholes that penetrated the Carnmenellis Granite at Carwynnen Quarry to depths of 150 to 700 m. They noted that the near surface granites were characterised by frequent sub-horizontal stress relief joints but that these became infrequent beyond about 60 m below surface. No hydraulic testing was however carried out in this upper zone as the work was aimed at characterising the permeability of granites at depth for a prospective repository. Hydraulic testing showed that hydraulic aperture values were about an order of magnitude higher in some borehole sections than in others. These features were considered to have a significant effect on the overall permeability of the granite. Average hydraulic conductivity values for the two boreholes considered the most representative of the granite at the site were 0.01 m/d and 0.003 m/d but were 0.0018 m/d and 0.0017 m/d if the major hydraulic features were excluded.

Granites at the depths at which packer testing took place are likely to be relatively unweathered and the hydraulic conductivity results thus obtained not particularly representative of the near surface granite normally considered to constitute the effective aquifer. The existence of such marked variations in the hydraulic properties of fractures is however likely to be applicable to the weathered mantle too in that only some of the fractures which are penetrated contribute significantly to total flow in a borehole or well.

10.3.3.5 *Pumping test results*

Data availability

Pumping test results are available for 18 boreholes that penetrate igneous rocks. All but one of the sites is located in the south-west of England, the exception being at Walkers House Farm located east of Hinkley, Leicestershire [SP 4946 9381]. Although the database indicates that this borehole was drilled in granite it is more likely to have penetrated diorite. A single test is also available for a borehole which penetrated pillow lavas at Trelaske Barton in Cornwall [SX 2867 8065].

Most results come from granites in Devon and Cornwall; ten on Dartmoor, three on the Carnmenellis Granite, one on St Austell and two on the Lands End outcrop. Transmissivities are available for most sites except for two of the Dartmoor and the two Lands End sites, where only specific capacities can be calculated. A single storage coefficient is available for one of the Dartmoor sites but the value is so large (0.1) as to be doubtful.

Pumping test discharge rates for the igneous pumping tests ranged from 14 m^3/d to 220 m^3/d although the majority were in the range between 40 and 80 m^3/d.

Specific capacity and transmissivity

Transmissivities and specific capacities determined from the pumping tests are summarised in Table 10.5 and presented graphically in Figures 10.4 and 10.5. The data set includes the diorite borehole in the Midlands and the pillow lavas, which provided transmissivities of 49.5 and 42 m^2/d and specific capacities of 17 and 54 $m^3/d/m$ respectively. The transmissivities are in fact the two largest in the data set but the specific capacity values are within the range obtained for the granite sites. Excluding the two non-granitic transmissivity values would give a slightly lower geometric mean.

The range of granite transmissivities is from 0.1 to 26 m^2/d; within the limited data set, there are no significant variations in values between the outcrop areas in south-west England. No relationship between specific capacity and transmissivity values can be observed (Figure 10.6).

Hartley (1998) also provided specific capacity and transmissivity data for seven pumping tests. Transmissivity values ranged from 0.7 to 7 m^2/d with specific capacities from 1.2 to 42 $m^3/d/m$.

There are pumping test results for three sites located on the Lizard peninsula; one borehole penetrating hornblende schists and two penetrating Lizard series rocks. Transmissivity and specific capacity values for the hornblende schist were 7 m^2/d and 29 $m^3/d/m$ respectively. For the Lizard series sites, transmissivities and specific capacities range from 5 to 13 m^2/d and 4 to 8 $m^3/d/m$ respectively.

10.3.3.6 *Yield data*

Information, regarding borehole and well yields from igneous rocks, is only available for the intrusions located in south-west England. Elsewhere groundwater from these rocks does not appear to be widely used, although undoubtedly yields capable of meeting small domestic requirements can be secured.

Yields obtained from boreholes and wells penetrating the granites of south-west England are dependent on the number, size and lateral extent of intersected fracture systems. Yields are therefore highly variable and only rarely of significant magnitude. In some cases yields decline with time as pumping depletes storage which is limited by a finite fracture system. There is anecdotal evidence from tin-mining operations that mines driven into the contact aureole (local name killas) tended to be wetter than those in the granites themselves, often requiring extensive dewatering.

Borehole depths in the Lands End Granite outcrop generally range from 15 to 35 m, final depths often being dictated by the penetration of a number of water bearing fractures. The mean annual yield of boreholes in this area is approximately 30 m^3/d with a 25% probability of the yield being less than 15 m^3/d (Monkhouse, 1981).

The mean yield determined for 73 boreholes penetrating the Carnmenellis Granite was 37 m^3/d, with about a 20% probability of the yield being less than 19 m^3/d (Leveridge et al., 1990). Similar yields appear to be available from boreholes penetrating the St Austell Granite outcrop. On the Dartmoor outcrop, small yields of up to 26 m^3/d are commonly available, occasionally ranging up to 44 m^3/d. Yields in the range of 0.5 to 7 m^3/d were reported for the Dartmoor granites by Tubb (1982), as well as yields in the range of 1.5 to 9 m^3/d for other igneous and hard metamorphic rocks outcropping in Devon. Borehole diameters in all areas are commonly in the range of 100 to 150 mm.

Higher yields can occasionally be obtained where old mine workings are encountered. Enhanced water flows may also be encountered in parallel dykes (known as elvans) which cross cut the granite (particularly the Carnmenellis Granite) due to frequent micro fracturing present in the dykes (Smedley et al., 1989). Conversely, yields may be much reduced where kaolinisation has occurred along fractures thereby reducing the fracture permeability (British Geological

Table 10.5 Summary of aquifer properties results for igneous aquifers in England and Wales.

Igneous aquifers		
Total number of records	18	—
Number of transmissivity records	14	—
Minimum/maximum transmissivity value (m^2/d)	0.1	49.5
Arithmetic/geometric mean of transmissivity (m^2/d)	12.7	4.2
Median/interquartile range of transmissivity (m^2/d)	4.4	25.1
25/75 percentile of transmissivity (m^2/d)	0.9	26.0
Number of storage coefficient values	1	—
Minimum/maximum storage coefficient value	0.1*	0.1*
Number of specific capacity values ($m^3/d/m$)	18	—
Minimum/maximum specific capacity value ($m^3/d/m$)	0.75	204.6
Arithmetic/geometric mean of specific capacity values ($m^3/d/m$)	36.7	11.4
Median/interquartile range of specific capacity values ($m^3/d/m$)	9.3	46.4
25/75 percentile of specific capacity values ($m^3/d/m$)	2.9	49.3

* recorded but doubtful value.

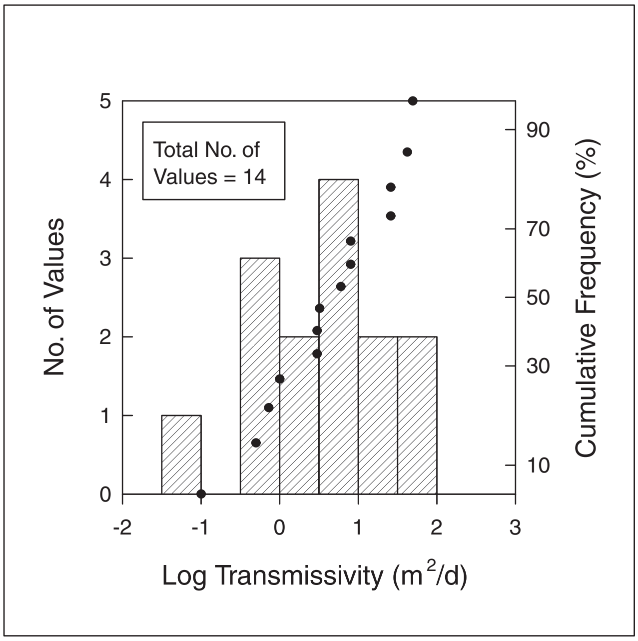

Figure 10.4 Distribution of transmissivity values for igneous aquifers in England and Wales.

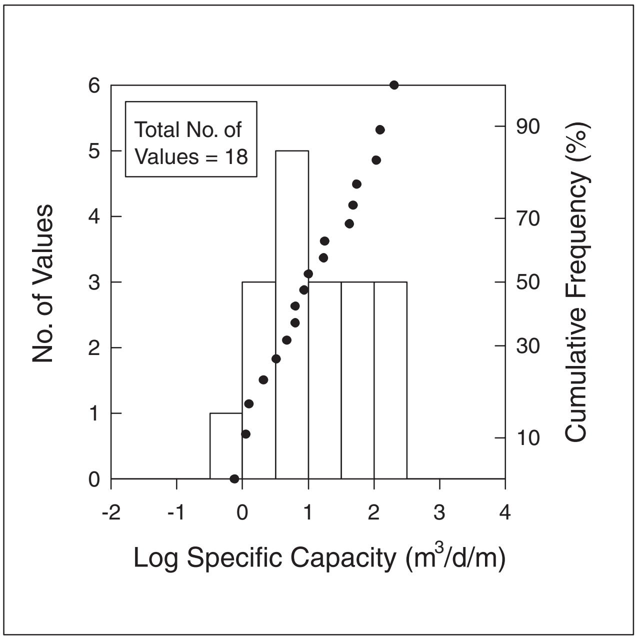

Figure 10.5 Distribution of specific capacity values for igneous aquifers in England and Wales.

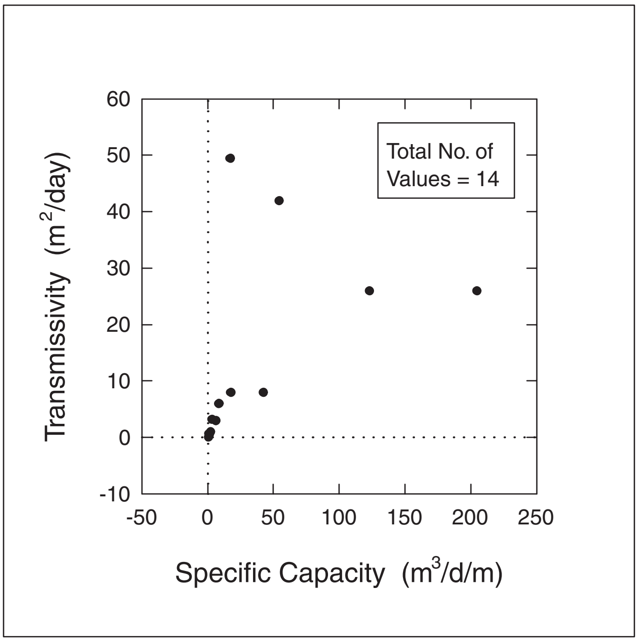

Figure 10.6 Correlation of transmissivity with specific capacity for igneous aquifers in England and Wales.

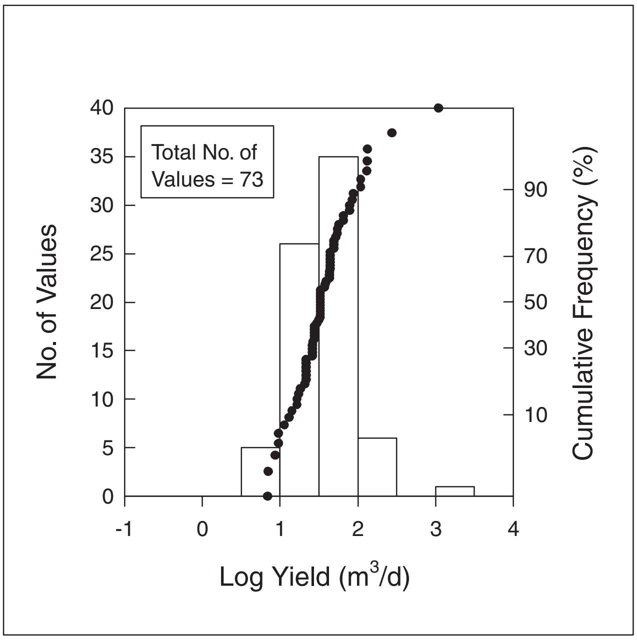

Figure 10.7 Distribution of yields for the granites of south-west England.

Table 10.6 Summary of aquifer yields for the granites of south-west England.

Number of yield values	73	—
Minimum/maximum yield value (m^3/d)	7	1091
Arithmetic/geometric mean of yield (m^3/d)	58.4	35.6
Median/interquartile range of yield (m^3/d)	32.8	27.6
25/75 percentile of yield (m^3/d)	21.6	49.2

Survey, 1989). At higher elevations, fractures capable of bearing water are commonly present although the depth of weathering may be minimal. Although such fracture systems are commonly dry, or may only constitute transitory perched aquifers due to rapid drainage, they can act as conduits for recharge to aquifer horizons at lower elevations. Regional groundwater flows are generally from granite outcrops on high ground outwards in a roughly radial pattern. Hydraulic gradients are generally steep, again indicating low permeability (British Geological Survey, 1989).

Seventy three pumping test results are available in the Aquifer Properties Database for boreholes penetrating granites in south-west England. Table 10.6 and Figure 10.7 summarise the results. Although the range is from 7 to 1091 m^3/d, the geometric mean is only 35.6 m^3/d, with an interquartile range from 21.6 to 49.2 m^3/d suggesting the values are predominantly at the lower end of this range. The values are very similar to those for the Carnmenellis Granite (Leveridge et al., 1990).

10.3.3.7 *Controls on permeability and transmissivity*

The main control on permeability and transmissivity is the extent of fracturing, and the degree to which the fractures have been weathered. Intrusive igneous rocks can be highly fractured and have often been subject to prolonged periods of complex alteration. The weathered carapace at outcrop is highly variable; it is often several metres thick in valleys but may be thin or absent in upland locations (Buckley and Cripps, 1989). The degree of fracturing is often enhanced by the weathering process, so the weathered mantle tends to be the most permeable zone except where rock decay is so advanced that the aluminosilicate minerals have decayed to clay minerals, as in kaolinised zones. The occurrence of open water bearing fractures is also greatest at shallower depths with permeability declining rapidly with depth, as fractures become tighter and less common. This marked reduction in permeability with depth effectively imposes a base to the aquifer, commonly quoted as occurring at 30 to 40 m below ground level.

There is, however, no doubt that water-bearing fractures occur at greater depths. Supporting evidence for this observation is not available from British sources, but downhole televiewer and lithologic logs for a borehole in granite-intruded schist in New Hampshire, USA illustrate this and are shown in Figure 10.8 (Shapiro, 1993). Although there are numerous fractures to depths in excess of 85 m, hydraulic conductivities determined by injection tests below 15 m depth are universally low: 10^{-2} to 10^{-6} m/d or lower. These values would not be sufficient to render the rock productive for water supply purposes.

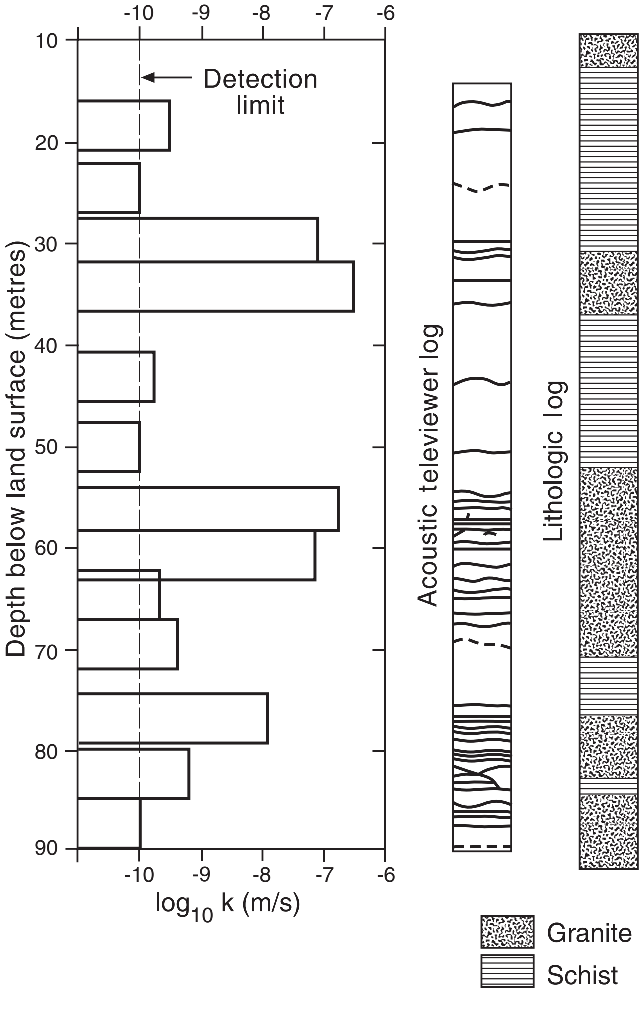

Figure 10.8 Hydraulic conductivity, acoustic televiewer, and lithologic logs for a borehole in granite-intruded schist in Grafton County, New Hampshire, USA (after Shapiro, 1993).

On the Carnmenellis Granite outcrop boreholes have a 95% probability of striking water bearing fractures within 20 m of surface with little prospect of a water strike below 30 m (British Geological Survey, 1989). Fracture permeability is however developed in a preferred orientation controlled by the maximum horizontal stress regime. The most dilated and therefore most important water bearing fractures are oriented north–south or north-north-west to south-south-east at about 15° to the maximum horizontal stress direction (Edmunds et al., 1989). Mineral lodes orientated east-north-east to west-south-west and dykes (elvans) may also be water bearing where sufficient fracture permeability exists (Edmunds et al., 1989). Heath and Durrance (1985) noted that the near surface Carnmenellis Granites were characterised by frequent sub-horizontal stress relief joints but that these became infrequent beyond about 60 m below surface.

Banks et al. (1992) reported that information derived from tunnelling operations in granites, gneiss and pegmatites in south-east Norway indicated that larger water inflows were not associated with major zones of fracturing and crushing (located by aerial photographs and seismic techniques) as may have been expected. It was postulated that these zones may once have been highly transmissive but a high contact area between the breccias or rock flour and water/hydrothermal fluids had resulted in a rapid alteration of minerals to clays and consequent reduction in transmissivity. Major inflows predominantly occurred from individual continuous joints in which the two planar parallel sides were considered to present less opportunity for rock-groundwater interaction, resulting in more limited mineral alteration. Inflows from individual fractures ranged widely from 7 to 245 m^3/d. It is entirely probable that similar features occur in the igneous rocks of England and Wales, and such phenomena would influence the success (or failure) of boreholes sited to intersect fault zones visible at surface or located via remote sensing or geophysical techniques.

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BGS Technical Report WD/00/04
Environment Agency R & D Publication 68

The physical properties of minor aquifers in
England and Wales