John Bloomfield

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Fracturing and the hydrogeology of the Permo-Triassic sandstones in England and Wales

D J Allen, J P Bloomfield, B R Gibbs and S J Wagstaff
with contributions by J A Barker[1] and N Robinson[1]

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BRITISH GEOLOGICAL SURVEY

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Statement of use
This report provides an overview of the current concepts of fracturing in the Permo-Triassic sandstones and their implications for groundwater flow, and summarises existing hydrogeological data

Cover illustration
Fractures in the Helsby Sandstone Formation (Runcorn Hill Park, Runcorn, Cheshire)
Note compass for scale, 10cm

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EXECUTIVE SUMMARY

In the Permo-Triassic sandstones the role of fractures in fluid flow has not been clearly evaluated. Recently, a number of lines of evidence have suggested that the predominant mode of transport in the Permo-Triassic sandstone aquifer depends on the scale of observation. These include results from pumping tests and other hydraulic tests, geophysical logging and water chemistry surveys, and an increased appreciation of the complexity of fracturing in sandstones arising from geological surveys associated with hydrocarbon reservoir analysis and radioactive waste disposal. There is some evidence to indicate that there may be a transition from fracture dominated flow at smaller scales to matrix controlled flow and transport at larger scales. Unfortunately, there is generally little direct information on the distribution and character of the fractures, and even less direct information on, or observations of, preferential flow through the fractures in the Permo-Triassic sandstone aquifer. Consequently, the importance and extent of fracture flow is difficult to model. This has serious implications for both UK groundwater regulators and the water industry. For example, uncertainties related to possible preferential flow, limit the efficiency of management programmes because the regulator may have to rely unduly on the precautionary principal, and uncertainties about unpredictable water quality due to fracture flow has important cost implications for the water industry.

The purpose of the present scoping study is to provide an overview of the current concepts of fracturing in sandstones and their implications for groundwater flow, and to review existing hydrogeological data on fractures in the Permo-Triassic sandstone in a systematic manner. The report describes the generic characteristics of fracturing in sandstones, and the hydraulic and hydrogeological behaviour of fractures in porous sandstones. It identifies and evaluates appropriate techniques for improving our understanding of the geometry and hydraulic behaviour of the fractures (where the term "appropriate technique" is taken to mean techniques that are both suited to the hydrogeological problems being investigated and that are viable in the context of normal hydrogeological investigations), and collates and evaluates what information there is on the geometry and distribution of the fracture systems in the Permo-Triassic sandstone aquifer in England and Wales, and describes their affects on local and regional hydrogeology. It is concluded with a description of the principal geological and hydrogeological uncertainties associated with fracturing in the Permo-Triassic sandstone aquifer in England and Wales, and a summary of requirements for further research.

The two types of fracture that are most hydrogeologically significant are bedding plane features and faults. Bedding plane fractures are common in the aquifer in all areas of the country. They may develop along any mechanically weak bedding plane surface, but they appear to be preferentially developed at relatively shallow depths and at discrete lithological contacts such as shale-sandstone boundaries. This type of boundary is often associated with overbank deposits and may have a lateral extent of a few hundred metres. Bedding plane fractures in channel-fill sandstones generally only have a lateral extent of a few tens of metres. Bedding plane fractures appear to be most hydrogeologically significant at depths less 200 mbGL. While these fractures can radically affect the response of boreholes to pumping it is unclear how interconnected they are on a regional scale; however the present evidence suggests that while they may be ubiquitous they do not extend as hydraulically connected features for more than a few hundred metres.

Faults are common structures within the Permo-Triassic sandstones. Their lengths and throws may vary from less than a metre to tens of kilometres, but within a region they may exhibit scale-invariant (fractal) size, spacing and displacement characteristics. Consequently, it may be possible to predict some regional fault characteristics from local outcrops. Faults are complex structures whose geometry and style are as much a function of the matrix properties of the rocks they displace as they are of the deformation history of the fault. Faults are rarely planar features, they generally consist of multiple subparallel slip surfaces.

Significant grain size reduction associated with cataclastic deformation causes the development of fault gouge in the core of fault zones. Fault planes may be the site of cementation and shale smears may be incorporated into fault planes where faults displace shales and mudrocks. Marginal to the fault zone porosity may be increased by pervasive microfracturing of the matrix. Coarser, more porous, less well-cemented sandstones are particularly susceptible to the development of enhanced porosity. Hydraulically, faults have been interpreted as having a range of effects, from acting as recharge boundaries to causing the hydraulic isolation of blocks of aquifer. A recurring model (Fowles and Burley 1994, Gibson 1994, Knott 1994) is that of a central fault core comprising low permeability fault gouge, surrounded by a high permeability damage zone. Thus, potentially, faults can act as linear zones of high permeability and barriers to cross-flow at the same time.

Sand pumping is a significant problem in some production boreholes and individual case studies can relate pumped volumes to specific pumping regimes. However, there may be a variety of causes of sand pumping, e.g. development of poorly cemented horizons, of induced fractures, of bedding plane fractures and/or of faults. It is not yet possible to predict the occurrence of sand pumping as the phenomenon has not yet been systematically investigated.

It is suggested that in the near future research concentrates on two main areas; (i) the investigation of the likely extent of bedding plane fractures, particularly as potential routes for rapid transport of pollutants and, (ii) the investigation of the hydraulic characteristics of faults, in particular whether they are likely to act as barriers to pollutant migration, hydraulic barriers for resources or alternatively rapid transport routes or recharge boundaries. Other useful areas of research would be the interaction between bedding plane fractures and faults, and the hydraulic properties of joints, however these are at present regarded as having a lower priority.

Although we need to improve our general understanding of the nature and distribution of bedding plane fractures, there is a specific need to be able to understand why some are more hydraulically significant than others. In particular, important questions include: what is the typical lateral extent of bedding plane fractures, and what are the physical controls on lateral extent? What constitutes hydraulically significant bedding plane fractures, what proportion of bedding plane fractures are hydrogeologically significant and to what extent is channelling significant? Additionally, can bedding plane fractures and hydraulically significant bedding plane fractures be correlated with parameters such as depth, or with lithology in a given region, catchment, or site, and if so how and why do these correlations vary and can we make any informed predictions concerning the distribution of hydraulically significant bedding plane fractures given the geology and location?

The main issue with faults is to improve our understanding of their hydraulic effects, e.g whether faults may act as planes of low permeability bordered by damage zones of high permeability. Important questions include: Can it be demonstrated that, in general terms, the relationship K(fault damage zone)>K (undisturbed aquifer)>K(fault core) is valid? If so, what are the controls on the three types of permeability? For example, how are they affected (relatively) by the proportion and distribution of argillaceous material, by fault type or by throw? In addition, can critical fault displacements be recognised on a local or regional basis, where faults with displacements equal or greater to the critical displacement act as barriers and how does permeability associated with faulting vary with depth or with vertical variations in lithology?

1. INTRODUCTION

1.1 Background

All the major aquifers in the United Kingdom are fractured to some extent, and this may result in highly heterogeneous flow systems at different scales, resulting in difficulties in predicting both aquifer physical properties and pollutant transport phenomena. Despite a number of studies, for example Price (1982) and Robins and Buckley (1986), the role of fractures in fluid flow in the Permo-Triassic sandstones has not been clearly evaluated. Opinions have varied in the past as to the importance of fracture, as compared with matrix, components of flow. Recently, a number of lines of evidence have suggested that the predominant mode of advective transport in the Permo-Triassic sandstone aquifer depends on the scale of observation (e.g. borehole, site, catchment, or regional). Based on the results from pumping tests and other hydraulic tests, geophysical logging and water chemistry surveys, and an increased appreciation of the complexity of fracturing in sandstones, there is some evidence to indicate that there may be a transition from fracture dominated flow at smaller scales to matrix controlled flow and transport at larger scales. In addition any transition in the dominant mode of transport will be complicated by the (often significant) local and regional variations in the hydrogeological characteristics of the matrix.

Unfortunately, there is generally little direct information on the distribution and character of the fractures, and even less direct information on, or observations of, preferential flow through the fractures in the Permo-Triassic sandstone aquifer. Consequently, the importance and extent of fracture flow is difficult to model and there is significant uncertainty about the hydraulic behaviour of the aquifer at the borehole to catchment scales. This has implications for both UK groundwater regulators and the water industry. For example, uncertainties related to possible preferential flow, limit the efficiency of management programmes because the regulator may have to rely unduly on the precautionary principal, and uncertainties about unpredictable water quality due to fracture flow has important cost implications for the water industry.

As part of a much larger groundwater R&D agenda, Grey *et al.* (1995) proposed that a three year project combining field characterisation studies of fractures, pumping tests, tracer tests and appropriate geophysical techniques should be developed to investigate the problem of the relationship between fracturing and hydrogeology in the Permo-Triassic sandstones. As a consequence of this recommendation the Environment Agency and BGS decided to undertake this scoping study with the purpose of evaluating the present state of information concerning the hydrogeological effects of fracturing in the Permo-Triassic sandstones, and to act as a possible precursor to larger studies.

1.2 Scope and Aims of the Report

A recent detailed study of the physical properties of the major aquifers in England and Wales (Allen *et. al.* 1997) highlighted the possible role of fracturing in the hydrogeology of the Permo-Triassic sandstone aquifer, and provided some site-specific evidence for the hydrogeological effects of fractures. The purpose of the present scoping study is to build on the work of Allen *et al.* (1997), to provide an overview of the current concepts of fracturing in sandstones and their implications for groundwater flow, and to review existing hydrogeological data on fractures in the Permo-Triassic sandstone in a systematic manner.

To this end five specific aims have been identified:

- to describe the generic characteristics of fracturing in sandstones, and the hydraulic and hydrogeological behaviour of fractures in porous sandstones,
- to identify and evaluate appropriate techniques for improving our understanding of the geometry and hydraulic behaviour of the fractures (where the term 'appropriate technique' is taken to mean techniques that are both suited to the hydrogeological problems being investigated and that are viable in the context of normal hydrogeological investigations),

- to collect, collate and evaluate information on the likely geometry and distribution of the fracture systems in the Permo-Triassic sandstone aquifer in England and Wales, and to describe their affects on local and regional hydrogeology,
- to identify the principal geological and hydrogeological uncertainties associated with fracturing in the Permo-Triassic sandstone aquifer in England and Wales, and
- to summarise requirements for further research.

1.3 Hydrogeological Problems and Information Requirements

It is useful to have an overview of the hydrogeological problems associated with fracturing in sandstones as they have shaped many of the lines of investigation and studies described in this report. This section briefly outlines the main problems associated with fracturing in the Permo-Triassic sandstone aquifer, and describes the sorts of information that may be required to address the problems. A feature of this section is that the problems appear to be both diverse and relatively poorly defined.

1.3.1 *Hydrogeological problems related to fracturing*

The general problem is that we have little understanding of the nature of fractures in the Permo-Triassic sandstone aquifer, or of the effects of the fractures on the physical hydraulic properties of the aquifer and on flows within the aquifer. Also, given that the matrix of the aquifer is usually permeable, the relationship between the hydraulic characteristics of the fractures and those of the matrix needs to be understood in order assess the relative contributions of fractures and matrix to flow in the sandstones. The uncertainties caused by fracturing in the Permo-Triassic sandstones are considered broadly to be associated with two types of structure; bedding-plane fractures, generally sub-horizontal, and faults, generally sub-vertical. (As will be shown, joints are thought to play a minor, or insignificant, role in the hydrogeology of the sandstones) These two types of structure can have significant effects on both the water resource and pollutant transport properties of the aquifer and both are affected by scale. Table 1.1 provides a simplified summary of the effects associated with the two broad classes of fracturing. It is of course likely that both types of fracture will interact, providing complex hydrogeological regimes.

Bedding-plane fractures and scale

It is a common feature of many aquifers, and the Permo-Triassic sandstone aquifer in particular, that a disparity is seen between core-scale, borehole scale and regional scale transmissivity data. The disparity between borehole and core scale results can often be ascribed to the effects of fractures assumed to be associated with bedding planes; data obtained at these two scales from the same borehole have often been used to quantify the fracture component of transmissivity measured at the borehole scale (Price *et al.* 1982). However, the relationship between transmissivities derived from pumping tests undertaken in boreholes and those used in regional models is very poorly understood. Given that pumping test values often vary significantly over short distances, whereas values used in regional models tend to be more uniform this may suggest the presence of ubiquitous but regionally unconnected fractures.

Table 1.1 Potential influence of bedding plane fractures and faults on hydrogeological processes.

	Bedding Plane Fractures	Faults
Local borehole effects	Potential significant increase in yield if intersected by borehole	Potential increase or decrease in yield if fault close to borehole
Regional effects	Minor to major increase in T depending on degree of interconnection of fractures	Potential hydraulic barriers Potential recharge boundary
Horizontal pollutant transport	Rapid flow to boreholes (scale depends on degree of fracture interconnection)	Rapid flow along fault zone
Vertical pollutant transport	Flow effects not significant but potential problems of ponding in unsaturated zone	Rapid flow in fault zone

The validity of this concept is poorly known, and if it is true it raises the question of over what scale are the fractures interconnected. Also, whatever the reason for the disparity between pumping test and model transmissivities the question remains as to the real meaning of the values at both scales.

Pollutant transport

The extent of individual fractures or interconnected fracture sets is important for the assessment of the rates of travel of pollutants in the aquifer. Where fractures are present and interconnected their high transmissivity and low porosity mean that polluted water is likely to travel very quickly through the aquifer. This could have a significant effect on the protection of water supplies. For example source protection zone definitions are currently based on times of travel and these may be radically shortened in areas where water can move rapidly through fractures. Also the extent to which fractures can conduct poor quality water from depth or from the surface is poorly known.

Borehole hydraulic behaviour

The effects of fractures on the hydraulic behaviour of production boreholes in the aquifer are poorly understood. For example, the possible contribution of fractures to delayed yield effects in pumping tests, and the likelihood of faults acting as hydraulic boundaries (either recharge or barrier types) is largely unknown.

Information problems

The lack of understanding of the nature and hydraulic effects of fracturing in the Permo-Triassic sandstone aquifer is both the result of a general paucity of information and a lack of research. A large number of pumping tests and core analyses have been performed in the sandstones. However, the hydraulic complexity of the aquifer (largely a result of its heterogeneity at the matrix scale, i.e. lithological and diagenetic variation, and at the catchment, sub-regional or basin-wide scale, i.e. tectonic structures) has only been investigated by a few, generally multidisciplinary, studies. It is essential that we develop a better understanding of the controls on the hydraulic complexity of the aquifer if we are to understand the movement of water in the aquifer.

The problem of a lack of information is compounded by the uncertainties associated with the data. In particular, there is a difficulty in using data from boreholes in parts of the aquifer where relatively unconsolidated material is present. This is because such material may be removed from the borehole wall during drilling or subsequent development, leaving a void near to the borehole which may mimic the effects of a fracture but which only exists for a short distance from a borehole. These intervals may show up on geophysical logs and may provide a zone of enhanced flow. This problem is important because much information concerning the presence and hydraulic effects of fractures is obtained from boreholes.

1.3.2 *Information requirements*

In broad terms, there are two types of information that would be required in order to understand the hydrogeological characteristics of the fractures in the sandstones, and therefore to address the problems outlined above. Firstly, the extent and geometry of the open fractures would need to be characterised and, secondly, the hydraulic behaviour of such fracture systems would need to be known. In addition, the properties of the matrix would need to be measured in order to be able to assess its significance to the overall hydraulic behaviour of the aquifer. The extent to which the above can be achieved will depend on the adequacy of the data (which will in turn generally depend on the availability of resources to explore the system) and of the theory available to exploit the data. The purpose of this report is mainly to concentrate on the adequacy of the data for the Permo-Triassic sandstones with reference to relevant areas of theory and techniques (for which a very large body of literature is available) .

Given the types of problems referred to above, certain types of information may assume a particular importance in the Permo-Triassic sandstone aquifer. For example, the degree to which fractures may form discrete, laterally continuous, features, the degree and nature of connectivity of different fracture sets, and the distribution and nature of apertures in a fracture network, are all likely to be of great significance for pollutant transport. Also, the effect of drilling on the nature of the fractures (or apparent fractures) close to boreholes is important in determining whether the results of hydraulic tests on boreholes are likely to adequately represent the material in the undisturbed parts of the aquifer. For faults, the hydraulic properties of the fault core and the nature and extent of the zone of damage around the core will be critical in assessing their likely hydrogeological characteristics.

Although the primary information requirements for understanding advective transport through a fracture network are an understanding of the geometry of the fracture system and the physics of flow in complex fracture arrays, most of the available information is indirect, usually based on inference from pumping tests, geophysical logging, modelling or other hydrogeological techniques. Consequently, an aim of this scoping study is to collate information, whether direct or indirect, that may have a bearing on our understanding of the hydrogeology of fractured Permo-Triassic sandstone.

1.4 The Permo-Triassic Sandstone Aquifer in a Geological and Hydrogeological Context

This section places the scoping study in a more general geological context, and also provides a brief hydrogeological background to the study.

1.4.1 *Geological context*

The Permo-Triassic sandstones outcrop in the south-west, central, north-east and north-west of England, and in the Vale of Clwyd (Figure 1.1), forming the onshore extensions of a number of major offshore sedimentary basins. Sandstone thicknesses may vary significantly, for example, the Sherwood Sandstone Group is up to 600 m thick in Lancashire, and near the northern edge of the Cheshire Basin the Permo-Triassic sandstones approach 1000 m in thickness. The Sherwood Sandstone Group is about 90 m thick in south Nottinghamshire, increasing to 180 m further north in Yorkshire. The combined thickness of Permo-Triassic sandstones in the Vale of Eden and along the Cumbrian coast exceeds 900 m (Day 1986). In the south-west and the north-east of England the sandstones dip to the east and become confined down dip by the Mercia Mudstone Group. In the west Midlands the sandstones occur in a number of basins and in the north-west it dips beneath the Irish Sea. A regional summary of the geology of the Permo-Triassic sandstones can be found in Allen *et al.* (1997).

The highly heterogeneous physical characteristics of the matrix of the Permo-Triassic sandstones are a function of the wide range of lithologies and complex diagenetic histories of the sandstones. The initial basal Permian deposits were coarse breccias and sandstones. Volcanic rocks are interbedded locally with these basal breccias. The breccias are generally overlain by coarse-grained, well-sorted, cross-bedded sandstones such as the Bridgnorth, Collyhurst and Penrith Sandstone Formations which have been interpreted as aeolian dunes, and which merge laterally into water-laid deposits. Upper Permian rocks are commonly represented by marine deposits, which comprise complex and variable formations of limestones, dolomites and evaporites; these grade upwards and laterally, towards the margins of the basins, into continental marls and sandstones. The basins initiated in the Permian continued to subside and thick clastic deposits accumulated forming the Sherwood Sandstone Group. Although largely of fluviatile origin, wind-blown deposits may also occur within the Sherwood Sandstone Group. The succession thins against older uplifted areas, such as the London Platform and the Pennines. A number of cycles of gradational grain-size occur within the sequence, and as a whole the grain-size decreases upwards. Subsequently, the mudstone and siltstone deposits of the

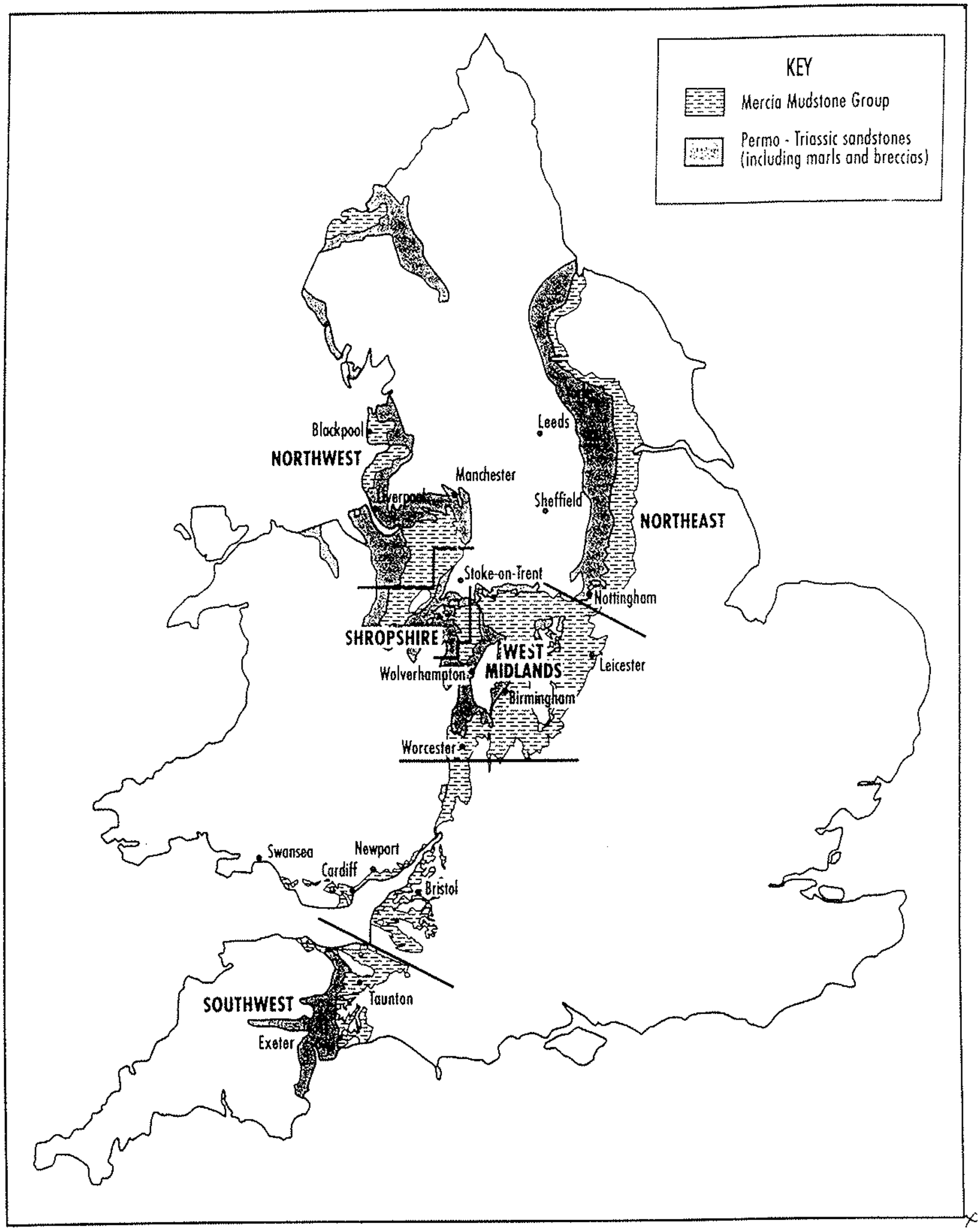

Figure 1.1 Outcrop of the Permo-Triassic Sandstones and Mercia Mudstone Group in England and Wales, showing the regional divisions selected (from Allen et al. 1997)

Mercia Mudstone Group covered the Sherwood Sandstone Group. Interbeds of halite, gypsum and anhydrite are present within the mudstone, and in places there are sandstone and siltstone horizons. Disseminated evaporite minerals are also present.

Variable stratigraphy across the country is caused by the nature of the fluvial sedimentation, with deposition switching to the east or west with time; so that the sediments in different areas were deposited at different times, though apparently at the same stratigraphic level. The Permo-Triassic deposits in the various basins have been given different names for coeval rocks; the general usage adopted is that described by Warrington *et al.* (1980), as illustrated in Figure 1.2.

The general absence of sedimentary compaction and the relatively high porosity of the Permo-Triassic sandstones suggest that, while they were initially cemented, much of the primary cementation has subsequently been dissolved. A variety of cements are now found, including calcium carbonate, dolomite, various forms of anhydrite, halite, iron oxide and clay minerals (Strong 1993). Anhydrite is found deep in the Wessex basin (e.g. the Winterbourne Kingston Borehole) and in north-east England at Cleethorpes. It is likely that here anhydrite dissolution has formed the bulk of the secondary porosity (Strong and Milodowski 1987; Knox *et al.* 1984). The presence of halite in Permo-Triassic rocks at depth in the Irish Sea Basin suggests that dissolution of a halite cement may have also contributed to the secondary porosity of the sandstone aquifers. In the north-west and in the Birmingham area there is less calcite towards the top of the aquifer than at depth. Deeper flowing waters tend to be supersaturated with calcite, presumably from mineral dissolution. In the deep basins, bedding-parallel and steep angled calcite veins are common. These mineral veins are at least partially weathered-out near the outcrop and so form open fractures along which water may flow. A variety of clay minerals may be present within pore spaces. For example kaolinite may be present as a late freshwater pore infilling. Illite can form webs across pores, reducing permeability by orders of magnitude without substantially affecting porosity, (although this mainly occurs in the saline part of the aquifer rather than near outcrop; for example the East Irish Sea Basin has an "illite affected zone", which formed beneath a paleo gas-water contact [Cotter and Barr 1975]).

The major structural features of the Permo-Triassic basins were initiated during a period of general extension and associated sedimentation. The largest structures in the Permo-Triassic sandstone basins are typically basin bounding faults. These features may have displacements of hundreds of metres. They are syn-sedimentary structures associated with large changes in sediment thicknesses, and their orientations are largely controlled by reactivation of earlier faults in the basement (south of the Variscan front they may overlie Variscan thrusts, north of the Variscan front they generally follow Caledonoid structures). Within the basins, arrays of smaller faults developed in response to local and regional subsidence and sedimentation patterns. These smaller faults are not necessarily parallel to the basin bounding faults. For example, in a recent review of the stratigraphy and structural evolution of the Cheshire Basin, Evans *et al.* (1993) have demonstrated that the basin is a faulted half-graben with NE-SW (Caledonoid) trend, controlled by subsidence along the Wem-Red Rock fault system in the south-east, with depositional onlap characterising the western margin (Figure 1.3). Smaller extensional faults in the Cheshire Basin generally trend north-south, or north-west - south-east (Earp and Taylor 1986).

The style of structures within of each of the major Permo-Triassic sandstone basins varies significantly between basins, principally due to differences in regional tectonic history. For example, the Carlisle and Worcester Basins overlie inverted former Variscan 'highs'; in contrast the Cheshire and Vale of Eden Permian Basins do not overlie inverted basins, but lie unconformably on Westphalian strata, and in eastern England the Permo-Triassic sandstones were deposited in association with the subsidence of the Southern North Sea Basin where sedimentation was not associated with major normal faulting (Holloway 1985). Local structures in each basin developed in response to a combination of local stress histories and locally significant

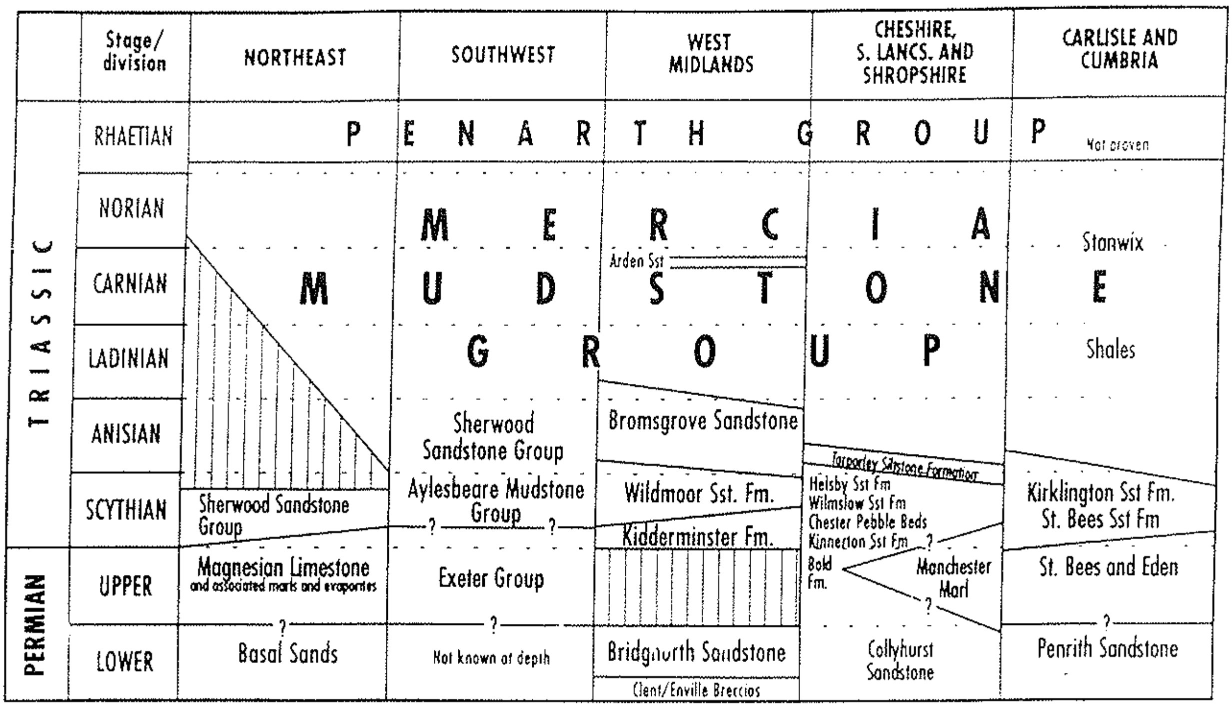

Figure 1.2 Regional-Triassic nomenclature (after Warrington *et al.* 1980)

variations in lithology. In addition, near surface structural features associated with weathering and unloading, and structures associated with recent groundwater circulation patterns may be as significant, hydrogeologically, as the larger sub-regional and regional structures. However, these local structures are likely to be even less predictable in their occurrence and characteristics than the larger structures.

1.4.2 *Hydrogeological context*

The Permian sandstones and the Triassic Sherwood Sandstone Group, which together comprise the Permo-Triassic sandstones, form a major aquifer in England and Wales. (The Permo-Triassic aquifer is also significant in south-west Scotland and in Northern Ireland) The Permian marls, where present, form an aquitard and separate the Permian sandstones from the overlying Triassic sandstones, however, limited water resources can be obtained locally from these rocks. The Mercia Mudstone Group, which overlies and confines the Sherwood Sandstone Group, is also an aquitard. However locally, especially around the mudstone and sandstone junction, there is considerable interlayering of sandstones and mudstones in fining upwards cycles (as for example in the Colwick Formation of central and eastern England).

The fluvial sequences, which form most of the Permo-Triassic sandstone aquifers, fine upwards from gravels and sometimes pebbles, to sands, silts and muds. Extensive clay horizons, resulting from the settling of flood overbank deposits, also occur, resulting in significant layered heterogeneity on the metre scale. Channel deposits may be continuous for significant distances potentially resulting in horizontal anisotropy with values higher along and down the channels. The aeolian Permian deposits have relatively low proportions of fine-grained material. They are cross-bedded on a metre scale, rather than the decimetre scale, which is more typical of the fluvial deposits. Fine-grained layers within the Permo-Triassic sandstone have lower hydraulic conductivities, and can act as confining layers. There is a general northerly decrease in grain size and (in very general terms) associated matrix hydraulic conductivity in the sediments in England.

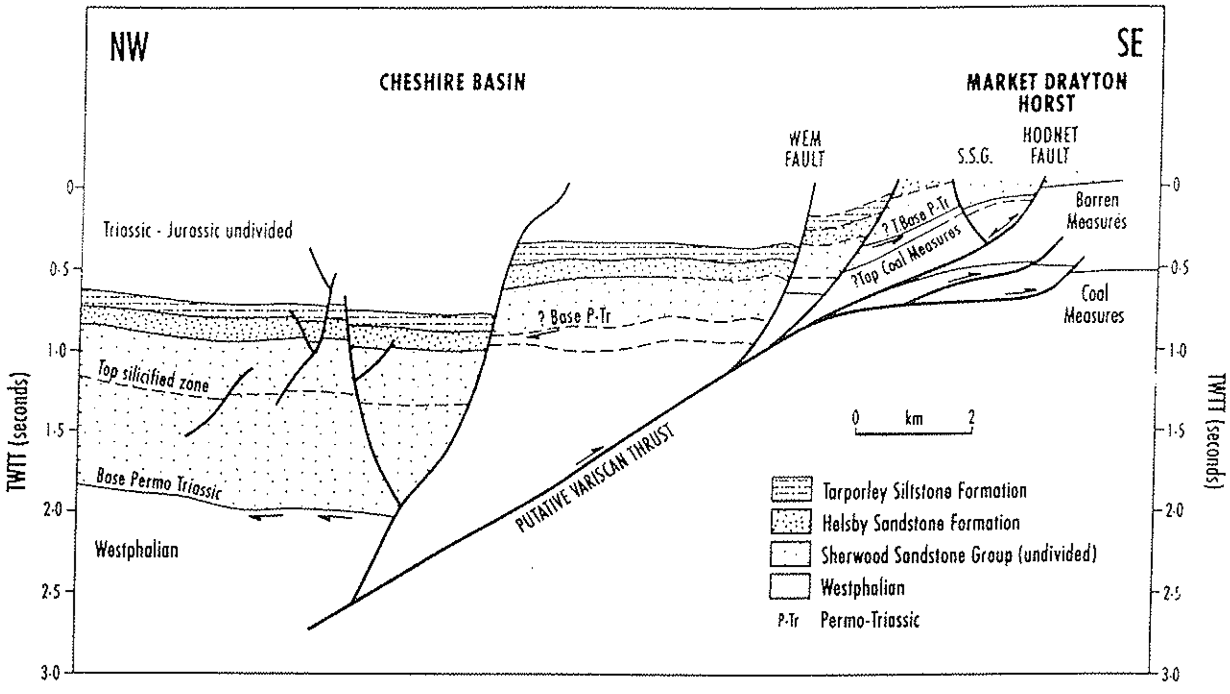

Figure 1.3 Example, from the Cheshire Basin, of the structure of a typical Permo-Triassic sandstone basin. The basin consists of a faulted half-graben controlled by subsidence along a NE-SW (Caledonoid) trending basin bounding fault (the Wem-Red Rock fault system) (after Evans *et al.* 1993).

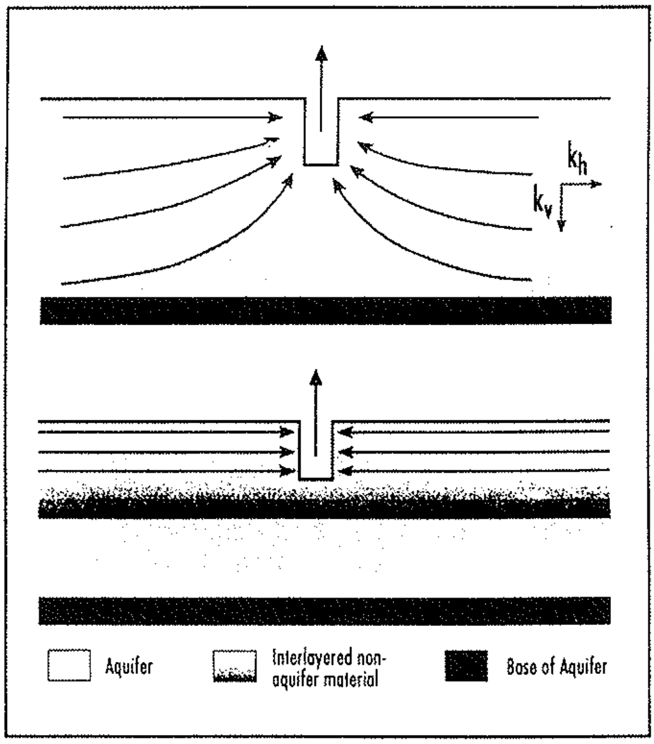

Figure 1.4 **Illustration of the role of anisotropic hydraulic conductivity caused by layered heterogeneity in controlling effective aquifer thickness where wells are not fully penetrating (from Allen *et al.* 1997)**

Fabric anisotropy at the matrix scale, principally caused by fine-scale laminations and interbedded sandstones and marls, is characteristic of the aquifer and causes considerable anisotropy in the hydraulic conductivity. The interlayering of marls can significantly reduce effective aquifer thickness where wells are not fully penetrating (Figure 1.4, Allen *et al.* 1997) and may locally cause 'double aquifer conditions', for example at Bridgnorth, Wolverhampton and Stourbridge.

1.5 Report Stucture

Section 2 is a review of some techniques of fracture characterisation, with emphasis on those most appropriate to hydrogeological investigations. The main body of the report, Section 3, describes and discuss the evidence for fracture controlled hydraulic behaviour in the Permo-Triassic sandstone aquifer. Section 4 presents a conceptual model of fracture architecture in the sandstones. It is based on both theoretical considerations of fracture distributions described in the Appendix and on the field observations in Section 3, and is used to make a series of potentially testable predictions concerning the behaviour of fractured sandstone aquifers. Section 5 summarises the findings of the scoping study, with particular emphasis placed on outstanding uncertainties in the nature and role of fractures in transport in the sandstones. Detailed definitions of fracture nomenclature, generic sandstone fracture and matrix characteristics and fracture distributions, along with descriptions of bedding plane fractures, joints, and faults, are provided in the Appendix. Also in the Appendix is a description of fracture hydraulics.

2. REVIEW OF TECHNIQUES OF FRACTURE CHARACTERISATION

A wide range of methods are available for characterising the geometry and hydraulics of fracture systems in sedimentary rocks. These methods include direct measurement of fracture characteristics at outcrop or on core material, indirect borehole geophysical techniques, for example acoustic and electrical methods, and a variety of hydraulic tests, including tracer and pumping tests. The methods were developed for a variety of reasons, for example, in response to the needs of the mineral exploration and hydrocarbon industries, as a result of nuclear waste disposal programmes and from groundwater water resource and protection studies. This section briefly describes and evaluates some of the techniques. It highlights the strengths and/or weaknesses of each technique and assesses their applicability to the investigation of fracture geometry and hydraulics in the Permo-Triassic sandstone aquifer. Table 2.1 summarises the techniques described below.

2.1 Geological Survey

Outcrop methods, although laborious, can give detailed quantitative information concerning fracture characteristics if there is adequate exposure. Field fracture surveys can provide data on fracture size, orientation, spacing and aperture as well as information on styles and types of fracture fill and fracture surface mineralisation. The forms of fracture size, spacing and aperture distributions can be obtained if sufficient data can be collected and it may be possible to characterise the scaling properties of each of these fracture parameters. Given adequate exposure, the extent to which joints, bedding plane fractures and faults are connected at various scales can be directly studied and semi-quantitative models of the fracture architecture can be established. Data from outcrop fracture surveys may be used to condition stochastic groundwater models. Outcrop surveys also enable fracture characteristics to be readily related to variations in matrix characteristics. For example, changes in joint intensity may relate to changes in sedimentary facies, or changes in fault style along the length of a fault zone may vary with changes in lithology.

Scan-line surveys are performed by placing a randomly oriented sample-line over the structures to be measured and only structures that intercept the sample- or scan-line are recorded. However, these measurements can be subject to significant biases (Priest and Hudson 1981). Firstly, a scan-line will tend to preferentially sample larger joint traces. Secondly, the largest traces may extend beyond the visible exposure,

Table 2.1 **Summary of fracture survey techniques, including geological, geophysical and surveys and hydrogeological techniques.**

A. Geological Survey Techniques		
Technique	Advantages	Disadvantages
1. Field survey i. Fracture mapping ii. Scan-line survey	Most valuable source of quantitative information on fracture distributions (size, orientation, spacing and apertures) essential to conditioning of groundwater models. Only direct method of assessing geometry of fracture network and connectivity of fracture sets. Best method of characterising relationships between fracturing, sedimentary architecture and matrix on structure of hydrogeologically significant features such as faults/fault zones.	Requires skilled staff, can be labour intensive and may be relatively expensive. Need good exposure of rocks at surface . When used in isolation difficult to extrapolate results to depth. Cannot provide direct information on groundwater flow.
2. Borehole logging i. Direct-core logging ii. Indirect - TV log	Core logs provide quantitative information on fracture orientation and spacing, on fracture surface mineralisation, and when combined with physical matrix properties measurements, flow logs and packer tests provide a detailed quantitative description of flow characteristics near the borehole.	Obtaining core is expensive. In highly fractured formations core loss may be significant. Core logs and downhole TV logs only provide information on fracturing adjacent to the borehole. TV logs can only be used in air-filled and clear water-filled boreholes. Borehole logs cannot provide reliable information on fracture apertures or fracture connectivity and on their own do not provide direct information of groundwater flow.

B. Geophysical Survey Techniques

Technique	Advantages	Disadvantages
1. Borehole-direct i. Borehole television ii. Formation microscanner iii. Azimuthal laterlog	Continuous digital logs of fracture occurrence in borehole (can be compared with core logs). Provide information on fracture orientation, spacing and aperture (ii and iii only), which can be combined with other logs and hydraulic tests.	Techniques are expensive, only provide information on fracture orientation, spacing and aperture adjacent to the borehole. They do not provide direct information on groundwater flow.
2. Borehole-indirect i. Caliper logs ii. Microresistivity logs iii. Dip meter iv. Sonic logs v. Gamma ray logs	Provide a range of continuous digital logs that can be correlated with direct geophysical logs.	Do not provide direct information on fracture characteristics and do not provide direct information on groundwater flow. Significant confusion is possible in interpretation of natural and induced features on indirect logs, e.g. borehole breakouts and caving of soft material. Some logs very sensitive to ambient borehole conditions, e.g. microresistivity, leading to uncertainties in interpretation.
3. Borehole-flow logs i. Impeller ii. Conductivity/temperature	Direct measurement of variation in flow in borehole with depth.	May be extremely difficult to calibrate, have a lower limit of detection that may be well above range of hydrogeological interest, cannot discriminate between single large flowing fractures and fractured intervals.
4. Surface	Used to locate large structures.	Very expensive, untested in the field of hydrogeology, thought to be of doubtful use in fracture characterisation.

C. Hydraulic Techniques		
Technique	Advantages	Disadvantages
1. Tracer tests i. Subregional ii. Between borehole iii. Dilution tests	Show hydraulic connection and flow rates within aquifer. Borehole dilution tests may provide information on vertical flows in boreholes and on location of active components of fracture network.	If no tracer is detected little can be determined about the nature of the system. Non-unique interpretation in case of detected tracer. Due to dilution effects, tracer tests on large scale may be infeasible in sandstones.
2. Hydraulic well tests i. Packer tests ii. Pumping tests	i. Provide quantitative estimates of borehole transmissivity. Most effective when run and with other hydraulic logs. Methods available ii. Provide quantitative estimates of quifer which if used in conjunction with i. above fracture flow.	i. Generally, only provide local hydraulic l difficulties. ii. Long-term pumping tests with observation ue interpretation may cause significant ambiguity if olume (dependent on test length).

consequently producing a known number of trace length measurements that are censored at some value dependent on the size of the exposure (censoring bias). Thirdly, the smallest joint trace lengths may be difficult or impossible to resolve at the measurement scale of the scan-line, leading to significant under sampling of small joint lengths (truncation bias). Finally, bias may be introduced due to obliquity of the joints to the scan-line. Theoretical corrections for these biases are available (Priest and Hudson 1981).

There are a number of reasons why outcrop surveys have not been used to characterise fracture distributions in the Permo-Triassic aquifers of England and Wales. Detailed fracture surveys are labour intensive and are consequently expensive. There is only limited exposure of Permo-Triassic rocks in England and Wales and the best exposures are not always near the areas of hydrogeological interest. For example, the best exposures may be along coastal cliff sections. Large disused quarries probably offer the most appropriate exposures for hydrogeological studies. A commonly voiced concern regarding field fracture surveys is that features that are seen at or near the ground surface do not reflect structures at depth in the aquifer. In addition, it is not clear how fractures characterised through field surveys can be used to define flow through the fracture network, *ie.* no *direct* observations of flow are obtained during field surveys. Despite these drawbacks detailed field surveys of fractures provide the most valuable source of information on fracture distributions, and when combined with sampling for core analysis, geophysical and flow logging methods and with pumping tests they may provide detailed information on the relationship between fractures and fracture flow.

Given the general absence of good surface exposure over much of the Permo-Triassic sandstone aquifer in England and Wales, and given the uncertainties involved in extrapolation of the results of field fracture surveys to aquifer conditions at depth, the most common approach to fracture characterisation is the use of borehole studies. For convenience, borehole techniques have been divided into techniques that involve direct and indirect geological observations. The most important of the direct observation techniques is core characterisation. This technique clearly provides the best quantitative information regarding fracture characteristics in close proximity to the borehole. However, core characterisation is not cheap and it may provide little information on the nature of fracturing away from the borehole. A large variety of indirect techniques of varying efficacy may be used for characterising fractured aquifers. These techniques include geophysical logging methods and hydraulic tests.

Assuming that fracturing is not so intense that there is significant core loss, the most effective method for detecting and characterising fractures immediately adjacent to a borehole is by direct observation of core material. Carefully taken whole core material can provide quantitative information on fracture dip and spacing, on fracture surface mineralisation characteristics and on the interactive flow capabilities of the fractures and the matrix. If the core is oriented then fracture azimuths can be obtained. When combined with measurements of the matrix properties of the core the data can be used to provide an in-depth quantitative description of the flow characteristics near the borehole. It cannot provide reliable information concerning fracture apertures or connectivity; however if multiple boreholes are studied it may be possible extrapolate features between boreholes.

Downhole photographic and television cameras may be used to provide direct qualitative information on physical features such as borehole condition, bedding planes, joints and faults and if the downhole tool is equipped with an orientation device then semi-quantitative data on fracture orientation can be obtained. A drawback to this technique is that the method can only be used in air-filled or clear water-filled boreholes. The picture quality tends to fall off with increased well diameter, and difficulties in interpreting the pictures means that they are best combined with other geophysical logs (Brandon 1986). Additionally, if there is any drilling mud cake on the well wall then this may significantly impede the use of downhole cameras.

Impression packers are inflatable bladders coated with pliable material. The unpressurised bladder is placed in the borehole and inflated. As the soft coating is pressed against the well bore it conforms to the rugosity of the borehole, including fractures. Subsequent observation of the packer coating can aid in the physical characterisation of the fracture system; however the technique is likely to be of limited use for detecting relatively small fractures in hydrocarbon reservoirs or aquifers. Also, very large or irregular well bores that are characteristic of many fractured formations can cause overextension and blowouts of the impression packers, making the technique somewhat unreliable.

2.2 Geophysical Methods

There are a variety of geophysical methods that can be used to characterise fractures in sedimentary rocks. Surface geophysical techniques, such as shallow seismic surveys, ground penetrating radar and azimuthal resistivity may be used to establish the position of larger faults in a region or may provide an indication of the density of fracturing and the orientation/azimuth of the major fracture sets. However, they are poor at imaging individual fractures and fracture connectivity characteristics and it is difficult to correlate the results with hydraulic information. The techniques are essentially untested in the field of hydrogeology and are of doubtful use in fracture characterisation and are not considered further. Borehole geophysical tools can be used to characterise individual fractures and fracture zones that intersect the borehole and these observations can be correlated with flow logs or the result of pumping or packer tests. However, borehole geophysics provides little information of the structure away from the borehole and essentially provides 2-D data. The main geophysical methods that may be used in the characterisation of fractured sandstone aquifers are described in the following sections.

2.2.1 *Borehole geophysics*

Borehole geophysics techniques are widely used in hydrogeological investigations. The methods employed were developed primarily in the petroleum industry where logging of oil and gas wells is routine; geophysical logging of some variety is now routine for most boreholes related to groundwater investigations, but techniques specifically aimed at fracture characterisation generally are much more limited. The following discussion concentrates on techniques that are, or are likely to be, of use in the evaluation of fractures, and is not a comprehensive review of borehole geophysics. Table 2.1 (after Jouanna 1993) summarises some of the main techniques and their applicability to fracture detection on open boreholes. Routine geophysical logs provide some information on the presence of fractures, but the evidence is usually weak and there can be confusion in interpretation of natural and induced features on indirect logs. Consequently, the hydrocarbons industry has developed a range of borehole imaging techniques in which the fractures can be 'directly' observed; these include the Borehole Televiewer and the Formation Microscanner. TV logs, although not extensively used in the hydrocarbons industry, are sometimes used in groundwater site investigations.

The borehole televiewer provides a continuous image of the acoustic response of the borehole face where open fractures appear as contrasting features in the matrix. It does not provide information on fracture aperture, but because it is an oriented tool, fracture orientation can be determined. Planar dipping fractures intersecting the borehole appear as images with a sinusoid form, from which azimuth and dip can be calculated. In contrast, two other techniques can provide estimates of fracture aperture and also give the fracture orientation. The Formation Microscanner is an electrical imaging tool consisting of several pads containing button electrodes that measure the microresistivity of the surface of the borehole. Images are obtained by displaying resistivity using grey levels. Resulting contrasts are coded, e.g. open fractures filled with conductive fluids appear as dark lines on the images and cemented fractures filled with resistive minerals as white lines. The Azimuthal Laterlog measures azimuthal resistivity to a depth of a few centimetres and again contrasts in resistivity are converted into grey or colour scaled images. Note, all the techniques described above, apart from the TV logs, only work below liquid level.

Generally, indirect methods, such as caliper measurements, resistivity measurements, dipmeters, sonic logs and natural gamma ray spectrometry can only indicate the probable occurrence of fractured zones and zones of weak rock and rarely provide information on the attributes of individual fractures. It should also be noted that indirect methods have a number of other drawbacks; the technique may be non-unique in that phenomena other than fracturing may produce an apparent response in a log, closely spaced fractures will not be resolved, there is little or no information regarding fracture orientation and generally the vertical resolution is poor. Despite this they provide an invaluable source of information because they are routine and relatively cheap with respect to field surveys and the imaging techniques. They are often the only methods available and they can be correlated with results from flow logs and hydraulic tests such as packer tests. In addition, sonic and resistivity methods may provide qualitative information on fracture apertures.

The diameter of uncased boreholes is usually measured by mechanical calipers and the resulting *caliper logs* can be used to detect zones of weak rock and by implication fracture zones. Preferential enlargement of the borehole may occur in fractured zones. However, this may be an unreliable indicator as borehole breakouts may also be associated with caving of unconsolidated material into the borehole, solution of minerals by the drilling fluid, rotation of the drill bit at a particular depth without downward drilling and, particularly in deeper holes, with an imbalance of stresses around the borehole. Other problems are that the measurements can be distorted if the tool is not centred or is inclined relative to the borehole axis and steeply dipping fractures can be registered as general enlargements if an arm of the tool runs in the fracture (e.g. Wilhelm *et al.* 1994). Also the tool does not indicate the direction of an enlargement. In addition caliper logs may detect horizontal fractures, but may miss short vertical fractures, depending on the orientation of their arms relative to the fracture system (Severn Water Authority 1972).

Microresistivity logs have depths of investigation of a few millimetres and respond to variations in the conductivity of the rock mass. Open fractures contain conducting groundwater can be identified by low resistivity readings compare with the resistivity of the matrix. However, this technique is very sensitive to borehole geometry and formation conditions (fluid properties) because of the shallowly penetrating nature of the microresistivity tool. Poor borehole conditions, a relatively high degree of damage and variable aperture, and heterogeneous formations may mean that this technique is of little practical use.

Dipmeters are borehole tools that use pads on the borehole walls to measure the microresistivity of the formation and produce *dipmeter logs*. Bedding and bedding dip can be determined by correlating microresistivity trends around the borehole and fractures are identified where the bedding curves exhibit local differences in the response of the dipmeter log. Clearly, not all anomalies can be attributed to fractures and irregular boreholes and features such as shale or marl breaks can also lead to anomalies in the response of the dipmeter log. In the hydrocarbon industry dipmeter logs are generally limited to fracture detection in relatively massive formations with good borehole conditions.

Sonic amplitude logs record the response of compressional and shear waves, generated by a sonic tool, to propagation through the rock mass adjacent to a borehole. The main affects on acoustic waves are reflection, mode conversion, and attenuation. A wide range of sonic techniques are available, but the most common is to generate acoustic waves that travel vertically in the direction of the borehole axis. In this geometry the compressional and shear waves are relatively unattenuated by low and high dip fractures, respectively, and orientation information is obtained if transmitter-receiver pairs cover the four quadrants of the borehole.

Gamma logs can be used to detect marly low permeability horizons; this is because clay layers are gamma ray emitters due to the presence of potassium, uranium and thorium. However, they also detect coarse sandstones that are rich in potassium feldspar, another high gamma emitter. They may indicate lithology changes associated with bedding plane fractures; and could have use within a suite of logs for locating the position of bedding plane fractures. Uranium may be deposited along fractures because it is very mobile, and gamma ray logs may recognise this

Fluid logs (ie. fluid electrical conductivity, fluid temperature measurements) are very useful indicators of fluid inflow - often associated with fracture zones. There are two common types of flowmeter - impeller and thermal. Both measure the vertical velocity of fluid in the borehole, either naturally occurring or induced by pumping of the borehole or adjacent boreholes. By flow logging and identifying changes in velocity (and taking into account borehole diameter changes using caliper logs), fluid inflows can be located and the relative magnitude of inflow can be determined. In conjunction with fluid electrical conductivity and temperature measurements and other log evidence flow logs can indicate fracturing. There have been many studies of flow logging (Paillet 1993). They generally reveal many 'enlargements' of 'fractures', but only a very small proportion may be hydrogeologically significant.

2.3 Hydraulic Tests

2.3.1 *Tracer tests*

Tracer testing, where material which can be detected in small concentrations (often dye, salt or bacteriophage) is added to groundwater in order to observe movement of the water, may offer a useful technique for detecting flow in fractures in the Permo-Triassic sandstones. If a tracer is injected at one point in the groundwater system and the time and form of its subsequent arrival at another point is monitored much useful information about the nature of the aquifer between the two points may theoretically be derived. For example forced gradient radial tracer tests from an observation borehole to a pumped borehole can be used (in principle) to determine longitudinal dispersivity, kinematic porosity, matrix diffusion, hydraulic conductivity and idealised fracture aperture as well as the spacing of individual layers or fracture zones (Ward *et al.* 1998).

Unfortunately, in practice tracer tests suffer from the problem that unless a tracer is detected little can be determined about the nature of the system. So, for example, the lack of observed tracer breakthrough between an observation borehole and a pumped borehole may indicate poor hydraulic connection between the two, or dilution of the tracer to below the detection limit, or simply that monitoring was not carried out for long enough.

Tracer testing in UK aquifers has mainly been carried out on the karstic Carboniferous Limestone in order to prove the connection between sinks and resurgences. In this environment it has proven to be a very useful technique because flow velocities are generally rapid and dilution of the tracer is relatively low since matrix porosities and permeabilities are very small and flow tends to occur in relatively discrete conduit systems. Some tracer testing has also been carried out in the Chalk aquifer, and again has been most successful where it has been used to prove connections between features such as sinkholes and springs. Some tracer work has been carried out in non-karstic Chalk and has been interpreted in terms of sets of fractures with different apertures (e.g. Ward 1989) but the research is as yet at an early stage.

Very few successful field-scale tracer tests appear to have been carried out in the Permo-Triassic sandstone aquifer (e.g. Coleby 1996) and the results are too few to draw significant conclusions. However the high matrix permeability and effective porosity of the sandstones compared with that of the Carboniferous Limestones and the Chalk suggests that tracer movement in the sandstones will be slow and that dilution will be a problem at the field scale. It is likely therefore that, given the constraints of detection limits and timescale of monitoring, tracer testing on a large (hundreds of metres) scale in the Permo-Triassic sandstones will generally be unfeasible.

On a smaller scale, such as between an observation borehole and a pumped borehole the technique may be useful but perhaps only in areas where the aquifer is fractured and where the matrix has low values of porosity and permeability.

On the scale of a single borehole, borehole dilution tests may provide a technique for assessing whether a fracture is 'active' (i.e. is connected to a set of hydraulically effective fractures) or is merely a 'local' feature which effectively is merely an enlargement of the borehole. In such a test a tracer is injected evenly over the open saturated thickness of the borehole and then the concentration of the tracer under natural hydraulic gradients is monitored. These tests can give information about vertical flows within a borehole and horizons of inflow and outflow (if the flow is mainly intergranular an average groundwater flow velocity can be calculated from the rate of tracer dilution). During such a test 'local' enlargements are unlikely to provide significant flow zones (whereas they might well appear to be active when the borehole is pumped and water flows into them from the matrix). Conversely 'active' fractures are more likely to provide conduits for water flow in natural unpumped conditions and this could be detected during the borehole dilution test.

In addition tracer tests can also be carried out on a laboratory scale on a block of aquifer material (which could be fractured). These tests, which are relatively quick to perform, can provide information about the detailed movement of water through the material under observation.

Where tracer tests give a positive result they can be modelled in a number of ways. Analysis of tracer tests through fractured media may, or may not, involve matrix diffusion. Within the Permo-Triassic Sandstones both matrix and fracture properties are likely to be important in the movement of a tracer. Analysis of tracer breakthrough for a fractured medium, but also allowing for matrix diffusion, is described, for example, by Maloszewski and Zuber (1993).

In view of the lack of tracer test data for the Permo-Triassic sandstone aquifer, it may be appropriate to collect and examine data from pollution incidents. These may be regarded as 'accidental tracer tests' and investigation of the movement of the pollution plume may provide valuable information concerning the effects of fractures. A problem with this approach however is that because of the accidental nature of the 'test' the data are likely to be poorer than those undertaken on purpose; in particular it may be difficult to establish when the pollution incident occurred.

2.3.2 *Hydraulic well tests*

Packer tests

Packer tests, commonly using straddle packers, or single packers as drilling proceeds, are used to measure the hydraulic properties of rock adjacent to isolated sections of a borehole and (particularly in conjunction with core data) can provide quantitative estimates of the contribution of fractures to total borehole transmissivity (e.g. Price *et al.* 1982). Analogue modelling of packer tests by Bliss and Rushton (1984) demonstrated that the influence of packer tests may extend for only around 10 m into the surrounding aquifer; packer testing results therefore are a measure of local formation properties only.

Tests are carried out at low excess pressures under laminar flow conditions. The pressure/flow relationship is analysed for each isolated section, and steady-state conditions are assumed. Water can either be pumped into the packer system (inflow test), or can be pumped out (outflow test). There may be problems associated with water injection in inflow tests; for example injected fines may clog pores or there may be chemical incompatibility between injected and ambient water that may lead to clay swelling or chemical deposition. Outflow tests do not have these problems and have the advantage of permitting water samples to be obtained for analysis.

Methods for performing double packer tests and their analysis are described by Price and Williams (1993), and potential problems and limitations of the method discussed. Where matrix flow only occurs then a formula obtained by Hvorslev (1951) is appropriate. However, if fracture rather than matrix flow is thought to be important, then a formula derived by Barker (1981) may be used. Bliss and Rushton (1984) used a mathematical model to confirm the validity, under appropriate conditions of the Barker (1981) and Hvorslev (1951) formulae.

Price (1994) has suggested a method for assessing the extent of a fracture in a double-porosity aquifer, using packer test data. The method is based on the assumption that, for a borehole which penetrates an isolated fracture, the rate of flow between the fracture and the borehole is limited by the rate at which water can transfer between the matrix and the fracture (under conditions of steady flow). For a simple horizontal disc-shaped fracture, and using simplifying assumptions, Price derived a formula which enabled the fracture radius to be determined using packer test specific capacity data and a knowledge of the matrix hydraulic conductivity.

Pumping tests

Much aquifer property information is obtained by the analysis of pumping test data obtained from boreholes. Large-scale (mainly constant rate) pumping tests have the advantage that they provide an estimate of the in situ properties of a relatively large volume of the aquifer. Short-term pumping tests lasting a few days on single boreholes are largely influenced by the local rather than regional aquifer characteristics of the sandstones. The local vertical and horizontal inhomogeneity and anisotropy of the aquifer arises principally from sedimentological variability, the fracture distribution, and saturated thickness variations. As well as responding to the pumping rate and aquifer characteristics, the potentiometric levels around the pumped borehole reflect interactions with local boundary conditions and local point sources and sinks. Long-term tests lasting for several weeks or months on a number of wells are necessary to directly determine the regional characteristics of an aquifer. In practice however, these are very rare due to the high costs involved (Reeves 1991).

Observation boreholes enable the development of the cone of depression around the pumping borehole to be more accurately defined, and therefore the average aquifer properties to be better determined. However in an aquifer like the Permo-Triassic sandstones with often pronounced layered heterogeneity the depth and position of observation points relative to the abstraction borehole can strongly influence the drawdowns observed. For example a shallow observation borehole penetrating only above a semi-confining layer may underestimate drawdown and overestimate transmissivity. A system of nested piezometers, which monitor the piezometric response at different depths at a given site, can be used to evaluate such effects, as well as determining the presence (or absence) of aquifer layering (Rushton and Howard 1982) and vertical interconnection within the aquifer. This can be used to infer the possible lack of vertical fractures.

The use of orthogonal lines of observation points during pumping tests to investigate lateral aquifer anisotropy is more likely to be influenced by local heterogeneity than regional anisotropy. For example one piezometer may sample a permeable zone which the abstraction borehole also penetrates, but which the other piezometers may not sample (Eggboro and Walthall 1986). The use of a number of observation boreholes oriented parallel and perpendicular to fracture orientation could indicate increased directional permeability parallel to fracture sets.

Unfortunately, the interpretation of the observed pumping test response can be ambiguous. There are numerous combinations of aquifer properties and associated boundary conditions that could produce any particular observed response. Frequently, the drawdown and recovery in abstraction boreholes only is measured. This can give an estimate of transmissivity, but is less accurate than observation borehole data for a variety of reasons. For example flow into and within the borehole may be non-laminar, poor borehole construction may result in significant well losses, and the actual pumping water level in a borehole may be dominated by only a single fracture. Water level readings from an abstraction borehole may therefore not accurately reflect the head in the aquifer.

Step tests can give transmissivity information, particularly if enough steps are used to define a clear trend of specific drawdown against discharge. Step tests are usually short and therefore the transmissivity measured tends to reflect the properties of the material near to the borehole, unlike longer constant rate tests that sample a significantly larger aquifer volume. Step tests also measure borehole efficiency but, unlike packer tests, yield no information about the distribution of the hydraulic conductivity. Their results are therefore more dependent on fractures encountered by an individual borehole, than the regional hydraulic conductivity of the aquifer. Step tests may indicate that flow occurs through discrete horizons. This can occur when an increase in pumping rate results in a larger than expected increase in drawdown, as a result of dewatering a productive fracture near the water table.

Careful collection and analysis of data from constant rate pumping tests in the Permo-Triassic sandstones should reveal the extent of double-porosity behaviour. Here, drawdown at early times depends only on the fracture system. Subsequently leakage from the matrix blocks decreases the rate of drawdown increase. Finally the leakage from the matrix reduces and the rate of increase of drawdown increases. Analysis of such behaviour, particularly if other information is available, such as the likely matrix block size (from geological studies), may help to elucidate the nature of fracture/matrix hydraulic interaction in the sandstones.

Borehole development and sand pumping

Abstraction borehole development can increase the apparent transmissivity of the aquifer close to the borehole due to the removal of fines and a consequent local increase of fracture size in the vicinity of the abstraction borehole. It could also induce the development of incipient fractures along poorly cemented horizons (Price 1994).

A large number of boreholes within the Permo-Triassic sandstones pump sand. This must result in the development of cavities within the borehole walls or surrounding area, and could result in the extension of incipient fractures. Careful monitoring of the amounts and type of material removed from a borehole by pumping could, if accompanied by geophysical logging and packer tests, provide information on the likely geometry and hydraulic properties of these types of voids.

2.4 Geochemical Techniques

Geochemical investigations can provide limited indirect evidence concerning fractures. Groundwater chemistry variations within an aquifer may indicate the likely degree of hydraulic interconnection of different parts of the aquifer. Groundwater quality studies may show that contamination is transmitted through the aquifer along rapid pathways, which could be fractures.

Some more sophisticated studies have been carried out, and others no doubt could be devised. Folger *et al.* (1996) investigated ^{222}Rn variations in wells within a fractured crystalline aquifer. They developed the work of Nelson *et al.* (1983), and assumed i.) that all the flow was through fractures, and ii.) that the ^{222}Rn was sourced from fracture walls. This implied that narrow fractures, with a small volume of water would have higher ^{222}Rn concentrations; and therefore that the concentration ^{222}Rn is inversely proportional to the fracture aperture. This implication is valid whilst all other factors remain constant, but fracture length, groundwater flow velocity and groundwater residence time are also expected to influence the ^{222}Rn concentration measured at a borehole. This method involving ^{222}Rn would have limited application to sandstones, where ^{222}Rn concentrations, and those of its parent isotope ^{226}Ra, are low, however, the principle of using the effect of the matrix on the chemistry of fracture water to indicate fracture size could be applied to sandstones, and might be worth further investigation.

2.5 Combination of Techniques

The methods described in the previous sections may individually suggest the presence of fractures affecting groundwater flow. However combinations of techniques offer far more powerful methods of understanding fracture hydraulic behaviour. For example a high calculated transmissivity from a packer test zone *may* suggest the presence of a fracture; however the suggestion could be made with much more confidence if previous geophysical borehole log data had suggested the presence of a void within the test zone (and core data indicating low matrix permeability would further support the interpretation). Away from boreholes the combination of tracer and hydraulic techniques may prove helpful in investigating fracture extents and the interpretation of any hydraulic, geophysical or geochemical data must be undertaken in the context of any geological information.

3. EVIDENCE FOR FRACTURE CONTROLLED HYDRAULIC PROPERTIES

There are a variety of lines of evidence for the role of fractures in the hydrogeology of the Permo-Triassic sandstones. This section reviews the evidence on a region-by-region basis. Regional sub-sections start with a précis of available information on the geological structure of the region and identify any important geological surveys in the area. Then various lines of evidence for fracture controlled hydraulic properties are reviewed; these may include surface and borehole geophysics (including flow logs), hydraulic testing, hydrograph data, geochemical evidence, and inferences from groundwater models. Any evidence for links between sand pumping and fracture development is also noted. The evidence is also summarised on a region-by region basis in a synoptic table (Table 3.1).

3.1 The North-East

The north-east region, illustrated in Figure 1.1, includes the Permo-Triassic sandstones of Yorkshire, Lincolnshire and Nottinghamshire. Table 3.1 summarises the evidence for fracture controlled hydraulic properties in the north-east region. The structure of the Permo-Triassic rocks in the Yorkshire and Durham area is relatively simple, with beds dipping gently to the east by up to 4°. Normal faults are present in several parts of the region, most of which can be related to the re-activation of pre-existing faults. In the Teeside area, the Permo-Triassic strata are disrupted by several major east-west trending faults, such as the Craven Fault, the Topcliffe Fault, the Butterknowle Fault and the West Hartlepool Fault. Further south, faults in the Thirsk area also tend to have an east-west trend, but north-east - south-west and north-west-south-east trending faults can be seen in the Knaresborough and Selby areas.

The Permo-Triassic rocks of Nottinghamshire have been subjected to faulting and gentle folding due to reactivation of pre-existing faults. There is a general dip to the east of around 1°, veering round to the south-east in the area around Nottingham. Undermining of the Sherwood Sandstone Group in the Nottinghamshire Coalfield has lead to subsidence and flexing of the sandstones at the edge of the worked area, resulting in the development of fractures up to 1 m wide at the ground surface. The mining-induced fractures can be traced to depths in excess of 30 m. This induced fracturing is likely to greatly increase the permeability of the Sherwood Sandstone Group in the affected areas. The underlying Permian mudstone formations of the Upper Permian tend to flex rather than fracture, so that the hydraulic base of the aquifer remains intact (Land 1952).

Small faults are thought to be present throughout the Permo-Triassic sandstones in the region, but due to the limited outcrop and the soft nature of the rock, are difficult to detect at the surface. In the north-east of England National Coal Board exploratory boreholes and investigation mapping provides the most detailed information on faults, but these are not necessarily near pumping boreholes for which there are transmissivity values (Allen *et al.* 1997).

3.1.1 *Geological surveys*

Geological maps of the region indicate faults at the Sherwood Sandstone Group-Permian contact or the Sherwood Sandstone Group-Mercia Mudstone Group contact, but faults are not generally indicated across the Sherwood Sandstone Group outcrop. Exceptions to this include the Topcliffe and Mid Craven faults. There is considerable indirect evidence from seismic studies and correlation of borehole logs that suggest an extensive system of faults, predominantly trending SW-NE, over the area of South Yorkshire and northward into the Vale of York. Seismic studies of the Selby Coalfield and the Barnsley area (British Coal) may provide detailed information on faulting at the base of the Sherwood Sandstone Group. To the west of the Sherwood Sandstone Group outcrop, there is evidence for many more faults, offsetting the feather edge of the sandstone, than are indicated on the Thirsk 1:50000 Geological Map Sheet 52. There also may be more faulting in the Ripon area than is suggested on published geological maps.

Table 3.1 Summary of types of evidence for the hydrogeological effects of fractures in the Permo-Triassic sandstones in England and Wales

	Region			
Type of evidence	North East	West Midland and Shropshire	North West	South West
Geological Surveys	Some faults and mining induced subsidence fractures mapped.	Hydrogeologically important faults probably under-represented on current maps.	Detailed Nirex studies at Sellafield (structural, sedimentological, mineralogical) have produced much fracture data; otherwise fractures probably under-represented on geological maps. Mineralogy of fracture surfaces may indicate flow.	Little geological investigation of fracturing in the region.
Geophysics	Surface geophysics - faults identified. Borehole geophysics - limited numbers of flow logs; some show fracture inflows.	Many logs but few flow logs. Evidence of fractures from a few CCTV logs.	Flow zones characterised by downhole logs at Sellafield. Elsewhere several hundred borehole logs, many indicating fracture influence.	Little geophysical data - inference of fracture flow at few sites.
Pumping Tests	Recharge boundary effects in a few tests interpreted as faults.	Limited packer tests suggest fractures. Pumping test evidence for low (mainly) and high T faults.	Packer-type tests at Sellafield and elsewhere show fracture effects. Some pumping test evidence for fracture flow and for both low and high T faults.	Fracture flow inferred to be important at a few sites (usually pumping test data unsuitable for fracture interpretation).

Models	Model values of T generally smaller and less variable than pumping test values	No good evidence.	Models have suggested lack of regional interconnection of fractures (Sellafield) and low K across faults (Fylde, Lower Mersey Basin)	Comparison of model, pumping test and core permeabilities suggests fractures not regionally interconnected.
Geochemistry	Some evidence of local saline water movement via faults and other fractures.	Little information. Saline water movement between boreholes at one site interpreted as via fractures.	Salinity anomalies thought to indicate fault flow. Water chemistry variations seen across faults. Tracer tests may indicate fractures.	No evidence for structural control on water chemistry.
Other	Hydrographs – some show 'peaky' response suggesting fracture flow. Sand pumping – occurs in some boreholes and may cause voids which could be interpreted as fractures.	Groundwater levels – significant head differences occasionally seen across faults. Anomalous stream flow losses and borehole grout requirements may suggest fractures. Sand pumping rare. Comparison between core and pumping test data at a few sites suggests fracture flow.	Groundwater levels - some evidence of aquifer compartmentalisation from hydrographs. Significant head differences sometimes seen across faults. Comparison between core and pumping test results often suggests fracture contribution to T. Sand pumping suggests void creation in poorly consolidated Wilmslow Sandstone Formation.	Hydrographs - Otter Sandstone Formation shows little evidence of 'flashy' response to recharge. Budleigh Salterton Pebble Beds show more rapid response.

3.1.2 *Surface geophysics*

A resistivity survey has been carried out in the Lower Dunsforth area that identified a series of faults separating horsts and grabens. Drilling into one graben proved over 250 m of sandstone, rather than the expected 100 m of Sherwood Sandstone aquifer, and throws of about 50 m have been inferred for the bounding faults. This is consistent with the throws identified on faults in the south of Yorkshire. Work has been carried out on the eastern edge of the Sherwood Sandstone Group, to the east of York, in the area of Stamford Bridge 35N 70E to 60N 80E. Typical fault offsets are thought to be up to 60 m (Aldrick, J. personal communication).

3.1.3 *Geophysical logs: flow logs*

There are limited published temperature, conductivity, caliper and sonic logs for the region (Robertson 1983, Buckley and Cripps 1990, 1991). In addition, Southern Science carried out a geophysical log survey in the Vale of York that included conductivity, temperature, caliper, formation and resistivity logs. Generally, fractures are not seen on caliper logs, though there are exceptions such as the New Lower Dunsforth borehole, where fractures are identifiable. The Southern Science logging was carried out on static, non pumping, observation boreholes that showed little natural vertical flow. However, logging of Hambleton borehole at Brayton Barff indicated some natural vertical flow (Aldrick, J. Personal communication).

There are limited flow logging data for pumping abstraction boreholes. Most boreholes in the Vale of York are of insufficient diameter to permit logging whilst pumping, so only New Lower Dunsforth [SE 445 643] and Bogbridge [SE 434 643] abstraction boreholes have flow logs. Flow logs exist for around 15 boreholes in the Selby and Doncaster areas. Generally flow logging has been carried out by measuring the flow velocity at certain depths to obtain a cumulative graph of velocity down the borehole. Generally the flow increases steadily towards the pump, though some boreholes (such as New Lower Dunsforth) show definite fracture features. Fractures are often seen in the upper part of the sandstone where more weathering has occurred, and generally there is little contribution from fractures below 120 m bgl.

Fractures were seen in TV logging of Hambleton borehole [SE 5580 3130] at Brayton Barff, Yorkshire where bedding planes were associated with borehole enlargement, and high-angle fractures were usually without borehole enlargement. Caliper logging did not identify all these fractures. Flow logging indicated inflow at discrete horizons with half of the total flow entering through a fracture at 55 m, and the remainder entering over a range of depths 58 to 59 m and 32 to 55 m (Buckley and Cripps 1991). The water entered the borehole through sub-horizontal fractures that coincided with soft marl-flake breccia bands. At Rainton [SE 374 750] sub-horizontal fractures are thought to be linked by sub-vertical tectonic fractures associated with the Topcliffe fault, so forming an area of high sandstone permeability (Reeves *et al.* 1974).

At Nutwell pumping station [SK 634 031] dynamic flow and conductivity logs indicated cold highly conductive water entering the borehole at discrete depth intervals. The water was inferred to be recent surface water. All the boreholes in the area showed anomalies at approximately the same depth, suggesting that the fractures lie along bedding planes rather than being steeply inclined. The source of the recently recharged water is thought to be runoff from the Markham Main Colliery 3 km to the north-west of the site (as shown by the water chemistry). Vertical leakage occurs where there is a high drift head and permeable drift, and the water is then transmitted along bedding plane fractures to the pumping site (Dodds 1986).

Rising chloride values in central Nottinghamshire pumped waters were investigated by Finch (1979). Surface and borehole geophysics indicated that aquifer contamination was occurring locally from acid, sometimes highly saline waters discharged from the local collieries. Nearly vertical fractures induced in the aquifer by the subsidence of underlying coal mines were probably responsible for rapid movement of saline Coal Measures water into and through the aquifer. Detailed flow measurements also confirmed mine water contributions to borehole flow from mine drainage and spoil tip water (Ireland 1978). The chemistry of pore waters in fractured horizons was seen to be much more saline (2200 mg/l Cl compared to a background value of ~200 mg/l), confirming preferential flow through fractures.

3.1.4 *Hydraulic testing*

Values of transmissivity obtained from standard step tests and constant rate tests in the region are generally independent of test length, although the storage value interpreted from the data may vary with the length of the test. This variation in storage coefficient can either be attributed to a delayed yield effect becoming apparent after some time, or the differing storage effects of fracture and matrix porosity. However, the relative importance of these two effects is not known. Boundary effects are rarely seen during step tests and constant rate tests, mainly because observation borehole data are not usually available.

Transmissivity values up to 600 m^2/d were obtained from short (less than one day) pumping tests for a number of boreholes in the area of Carlton in south Yorkshire (Parker *et al.* 1985). More reliable, longer tests (for Mill Lane [SE 655 246] and Hanger Lane [SE 638 242]) gave lower values of 350 and 400 m^2/d respectively. From this it was inferred i.) that longer tests with a wider cone of depression sampled, on average, a lower transmissivity, and ii.) that fractures locally intersected by boreholes provide a very high local transmissivity, but are not regionally interconnected.

At Carlton, on the basis of comparisons between core and field hydraulic conductivity, it appears that fracture flow is locally important for transmitting water to the Hanger Lane borehole, whereas matrix permeabilities appear to account for all of the transmissivity at Mill Lane (Parker *et al.* 1985).

A pumping test on the Eggborough No 3 borehole [SE 585 238], near the village of Hensall, is thought to be influenced by a local fault which was seen during drilling as a very large fracture which appeared near Eggborough boreholes No 1 and 2. Drawdown practically ceased after twelve hours pumping in borehole No 3 and after a day in boreholes No 1 and 2. Rapid equilibration of borehole water levels indicated that the fault was acting as a recharge boundary.

A series of group pumping tests have been performed in the Vale of York as part of the development of the Vale of York River Ouse Groundwater Augmentation Scheme. These are interesting as the development of an aquifer-wide cone of depression was monitored in over a dozen boreholes over an area of several kilometres. Within the group pumping test only a borehole at Rainton [SE 374 750], situated close to the Topcliffe fault, showed a definite boundary effect. A zone of high permeability, parallel to the fault, was inferred from the elongation of the cone of depression to parallel to the fault in an east-west direction. Another borehole, drilled to the south of the Topcliffe fault, but at a greater distance from the fault than the Rainton borehole, had a much lower yield than Rainton. This suggests that the aquifer is particularly permeable in the vicinity of (though not across) the Topcliffe fault (Aldrick, J. personal communication).

A tracer test has been carried out at Carlton (Yorkshire) in the Sherwood Sandstone. The unsaturated zone in this area is about 15 m thick, but is probably locally saturated due to leakage of effluent from a silage clamp. Tracing bacteriaphage from the clamp to a pumping station 300 m distant took about 200 days, giving a rate of travel of 1.5 m/d (Aldrick, J. personal communication).

Price and Williams (1993) used a combination of double packer tests and laboratory measurements of matrix permeability to assess the relative contribution of fracture flow to a borehole at Hambleton, North Yorkshire. They found that in general secondary permeability features were absent from the unlined portion of the borehole and that there was good agreement between laboratory and packer results. However, they noted four intervals with anomalously 'high' packer results. In these intervals it was inferred from geophysical logging and CCTV logs that the anomalously 'high' results can be explained either, as the result of secondary permeability features or of friable material not sampled for laboratory testing.

3.1.5 *Hydrograph data*

There are about 300 hydrographs for the region, although a number of borehole water levels are measured monthly and so the response to specific rainfall events is not seen. Most hydrographs exhibit an annual water level variation of 1 to 2 m, which can be modelled using a porosity of 15%. The hydrographs generally show a smooth water level variation; although some have a slightly peaky response, possibly due to fracture or bypass flow to the aquifer following rainfall events. Temporary saturation of the sandstone could also greatly increase the hydraulic conductivity of the aquifer and thus the rate of recharge and result is a 'peaky' hydrograph response.

3.1.6 *Geochemical studies*

There are considerable amounts of chemical data recorded in the region, but they have not generally been collated or interpreted. There is some evidence to suggest that faulting may influence local water quality. Ground water along the western feather edge of the sandstones often has a higher salinity (especially higher sulphate levels) than elsewhere within the aquifer. This could be due to faulting allowing progress of saline water from the underlying Permian Marls; either vertically along fault planes or horizontally where the sandstone is juxtaposed against the marl. Alternatively, the presence of some gypsum and marl at the base of the Sherwood Sandstone Group could result in higher salinities where the aquifer is thinnest. In the Selby area, there is localised upconing of saline groundwater into the base of the Sherwood Sandstone Group, especially along fault zones, where the sandstone is juxtaposed against the Upper and Middle Permian Marls. The groundwater head in the sandstone is lowered in areas of abstraction, and this results in an upward hydraulic gradient from the Permian Limestone to the Sherwood Sandstone Group which permits ingress of saline Permian groundwater into the sandstone, particularly along fault zones. Higher salinity water is also seen in the Lower Dunsforth area, also possibly associated with graben faulting.

A plume of high salinity groundwater has been observed near Boroughbridge. This is thought to be moving, at a rate of 20 Ml/d, from the base of the Sherwood Sandstone Group through a fracture system in the sandstones to a discharge point in the river Ure, via springs near Boroughbridge. The poorer quality water has been detected in a number of boreholes, including a monitoring borehole near the discharge point (Aldrick, J. personal communication).

3.1.7 *Mining induced subsidence fractures*

Rufford Lake [SK 648 652] regularly drains away down fractures, the scale of which have been increased by intensive undermining in the Coal Measures. Saline water from a colliery discharge stream enters the Rufford [SK 6322 6100] and Clipstone [SK 6031 6435] boreholes, through mining induced subsidence fractures (Fletcher, S. personal communication). Rainworth Water, a tributary of the River Maun that feeds Rufford Lake, also loses water through fractures. Chloride-rich colliery discharges to Rainworth Water are transmitted without adequate dilution into the aquifer by way of the fracture system, with migration of this contaminated groundwater occurring in a north-easterly direction (Howard Humphreys and Partners, 1990)

3.1.8 *Models*

There are two recent Groundwater Protection Zone (GPZ) models of the Vale of York. The Ainderby Steeple model covers the north of the Vale and the Lower Dunsforth model the south; they are thought to have limited use. A model of the Selby area uses a hydraulic conductivity of 4 m/d; this is similar to bulk hydraulic conductivity values determined from pumping tests. The models generally adequately represent the transmissivities of around 250 m^2/d found at the western edge of the aquifer (aquifer thickness ~60 m), and transmissivities of about 400 m^2/d to the east of the outcrop (effective aquifer thickness ~100 m). However, locally boreholes apparently penetrate the sandstone aquifer where it has transmissivities of 1000 m^2/d or greater, with occasional values of 1500 m^2/d. These equate to local bulk hydraulic conductivities of 6 to 8 m/d; which are generally greater than values used in models. One possible explanation for the difference is the *in-situ* development of fractures around abstraction boreholes and between abstraction and observation boreholes. Data for a pumping test carried out at Lower Dunsforth with several observation boreholes was plotted as drawdown versus r^2/T (r = distance to observation borehole, T = transmissivity interpreted from that observation borehole drawdown). A straight line was not obtained, suggesting that the permeability of the sandstone aquifer varied with distance from the Lower Dunsforth borehole (Aldrick, J. personal communication).

Groundwater resource models of the Nottingham area require transmissivity values often around half those observed in pumping tests. For example, the Nottingham model has transmissivity increasing from a minimum of 10 m^2/d at the feather edge to 550 m^2/d (in the north) and 1200 m^2/d (in the south) in the centre of the outcrop. The model transmissivity then decreases to 40 m^2/d (lowest 10 m^2/d) in the east as the aquifer becomes deeper and confined (Bishop and Rushton 1993). The model transmissivity value in the region of Edwinstowe [SK 635 682] is in the range 260 to 350 m^2/d (Bishop and Rushton 1993). This is substantially less than the pumping test transmissivity of 1500 m^2/d (equivalent to horizontal hydraulic conductivities in the range 60 to 36 m/d (depending on water level). These pumping test figures are large, and indicate extensive fracture flow at Edwinstowe and possibly also contributions from the aquifer beneath the borehole, which is feasible given the undermining and fracturing of the Sherwood Sandstone Group in the area (Satchell and Edworthy 1972).

Although important locally, the hydraulic effects of faults are not necessarily important when modelling at a regional scale. For example faulting is present in the Gainsborough area [SK 482 390], but does not cause effects which need to be accounted for in models (Fletcher, S. personal communication).

3.1.9 *Sand pumping*

The sandstone is generally cemented sufficiently for boreholes (typically drilled to depths of up to around 250 m) to be unscreened with only the Mercia Mudstone Group cased out. Locally, however, boreholes may pump sand and therefore require screening. This has been a particular problem in variably cemented, unconsolidated to friable horizons within the Vale of York. Generally, in Yorkshire large abstraction holes which are heavily pumped (i.e. 6000 to 10 000 m^3/d) have a 25% chance of encountering a sand problem.

A borehole constructed in the Eggborough area in 1926, produced of the order of several hundred tons of sand as a result of pumping. The borehole eventually collapsed and the fracture leading to the collapse was excavated. The fracture was dug out to a depth of 60 ft, had a north-west-south-east trend and was interpreted as a fault. Sand pumping has been investigated at a borehole in Lower Dunsforth, with collection of the sand pumped at different pumping rates and over different time intervals. Groundwater flow (and sand) originates from one fracture in the borehole and some basic calculations on the velocity and distance of sand movement along the fissure have been made (based on 3 m/s velocity to move sand - Aldrick, J. personal communication). The borehole produced a slug of sand on each start up of pumping.

In Nottinghamshire some boreholes regularly pump sand. If new holes are pumped for a few days at around 1½ times the intended pump rate they may yield large quantities of sand, but subsequently pump very little or no sand at the lower rate (Fletcher, S. personal communication).

3.2 West Midlands and Shropshire

The West Midlands and Shropshire region, illustrated in Figure 1.1, includes the Permo-Triassic sandstones from Worcester and Leicester in the south and east to Stoke-on-Trent in the north. Table 3.1 summarises the evidence for fracture controlled hydraulic properties in the region.

The Permo-Triassic sandstones in the region occur in a complex series of interconnected fault-bounded basins; the Stafford, Knowle, Worcester, Needwood and Hinckley Basins. These were initiated in the Permian and early Triassic, however, during Triassic times deposition gradually spilled over the basin margins onto adjacent highs leading to progressive onlap of later sediments. There has been no systematic survey of faults that may affect the hydrogeology of the sandstones in the region. It is thought likely that the current geological maps may under-record the occurrence of hydrogeologically significant structures.

3.2.1 *Hydraulically significant faults*

There are a variety of records of faults that act locally either to reduce or increase the hydraulic conductivity of the sandstones. The evidence for hydraulically significant structures is usually indirect, obtained from pumping tests, abrupt changes in water level variations, spring lines or from groundwater flow modelling. Although faulting can be inferred to increase transmissivity locally (for instance the productive Whitford borehole [SO 935 706] is situated on the Hagley fault [Black and Barker 1981]), there is generally more evidence for faults that reduce the conductivity of the sandstones.

Perhaps the most intensively studied structure in the region is the Copley Fault, near Nurton. Pumping of the Nurton borehole [SJ 831 007], 5 km south-east of Bridgnorth, led to a linear drawdown at the abstraction well that did not stabilise. The water level declined at a constant rate of 0.1 m/d, when pumped at 8340 m^3/d, and only the closest two of the twenty four observation sites were affected by the test (Fletcher 1989, 1994). Both were within 500 m of the abstraction borehole. It was inferred that the abstraction borehole penetrated a closed system with no lateral inflow replacing the water being removed. Radial flow modelling based on a 0.7 km^2 impermeable fault bounded block with 600 m^3/d recharge vertically through the surface layers reproduced the observed drawdown pattern. Although the presence of the impermeable Pattingham fault to the west of the borehole is known, impermeable bounding faults to the east, north and south of the borehole are only postulated.

Low permeability north-south striking faults are present at Croxton, Staffordshire [SJ 78973142]. At Burton on Trent [SK 250230], an impermeable fault is needed to explain observed drawdown behaviour. Impermeable faults to the west and east of the Bishton Farm borehole [SJ 803 017], near Albrighton in the Wolverhampton to Bridgnorth area, may account for the unexpectedly low yields within the Bromsgrove Sandstone Formation there. The drawdown from boreholes in this area is therefore likely to spread to the north and south (Fletcher 1985; 1989). Transmissivity is also reduced across the Birmingham Fault, which was modelled by Knipe *et al.* (1993) as a zone of reduced aquifer thickness.

An impermeable fault forming the eastern boundary of a Permo-Triassic sandstone block in the Featherstone area prevents groundwater flow westwards. Local groundwater levels are 30 m higher than those in the surrounding area. A spring line falls on the north - south trending Pattingham Fault, west of Nurton and north-west of Bridgnorth, which juxtaposes sandstones. The water table to the east of the fault is at levels in excess of 20 m higher than the water table to the west, indicating that it is impermeable (Fletcher 1994).

Where large displacements cause juxtaposition of permeable and impermeable strata, the hydraulic continuity across a fault can be broken or significantly reduced. For instance groundwater flow is affected at Hodnet, where the Hodnet Fault causes the Sherwood Sandstone Group to be set against the Mercia Mudstone Group (Fletcher 1977). Faults which do not interrupt sandstone continuity do not usually significantly affect groundwater flow (Fletcher, S. personal communication). Two low permeability intersecting faults at Hopton partially isolate a wedge of aquifer. Observation wells outside the wedge are not affected by pumping the Hopton borehole [SJ 5932 2662]. Groundwater flows into the wedge along its third side, which means that it does not empty like a bucket, as in the Nurton (West Midlands) example. At Harmer Hall [SJ 490200], Leaton, Shropshire, low permeability faults extending from the Mercia Mudstone are needed to explain the drawdown pattern. Current research about this is being conducted for Phase 3 of the Shropshire Groundwater Investigation.

3.2.2 *Mining induced subsidence fractures*

Mining induced subsidence fractures are present in the bed of the Rising Brook, a low flow stream in Cannock Chase. Flow losses occur over very short intervals, rather than uniformly along its length. There is significant fracturing associated with mining subsidence in the Nottingham area (also see Section 4.1). For example, large fractures opened up in the Ollerton area and Boughton PWS had to be closed. Severn Trent Water plc have maps of the distribution of the major fractures.

3.2.3 *Geophysical logging*

A variety of paper and digital geophysical logs are available for the region. Logs run are principally caliper, temperature, conductivity, gamma and resistivity. There has been little flow logging or sonic logging. CCTV logging has been undertaken occasionally, mainly in Shropshire. There are about 125 geophysical logs on the Environment Agency database, including 20 CCTV logs. At present, the Environment Agency, Midlands Region run ten to twenty logs each year.

Caliper and CCTV logging, together with core sample inspection, showed that fracturing of the aquifer exists at Hodnet Station [SJ 621 280]. A large near vertical fracture was present at a depth of 50 m and smaller fractures at 60 and 64 m. Differential temperature logs showed evidence of inflows at certain horizons in the Childs Ercall [SJ 664 233] and Helshaw Grange [SJ 632 292] boreholes (Severn River Authority 1972). Large fractures can be seen on the CCTV log of the Hopton Corner Observation borehole [SJ 601 269]. This borehole is close to the low permeability faults which hydraulically isolate the wedge of aquifer at Hopton [SJ 5932 2662]. At the Smethcote site [SJ 4991 2132], CCTV videos taken during Phase 3 of the Shropshire Groundwater Investigation, revealed vertical and subvertical fractures. The borehole had a high yield of 4 000 m^3/d with less than 0.5 m of associated drawdown (Fletcher, S. personal communication)

3.2.4 *Hydraulic testing*

Fracture flow has traditionally been thought to be more significant in the West Midlands than in Shropshire (Fletcher, S. personal communication). Transmissivities of 3000 m^2/d and above are not uncommon in the West Midlands, whereas values in Shropshire are typically 200-300 m^2/d, values more typical of intergranular flow (however pumping test data presented in Allen *et al.* (1997), suggest T values for the two regions have a similar ranges and similar geometric means).

Boreholes with exceptionally high yields are likely to have a component of fracture flow. Thus fractures are suspected at Frankston Locks [SJ 3662 3210], Shropshire. Wills (1976) describes Churchill Borehole, Stourbridge, which was poorly yielding until it hit a fracture.

The drawdown-time responses of four observation wells for a constant rate test at Lower Frankton [SJ 366 312], in the south Perry Pilot area of Shropshire, all show a confined response. The effects spread rapidly in the confined aquifer and it was inferred that drawdowns were soon influenced by the two barrier boundaries of the Whittington and Hordley Faults. The observation wells gave different transmissivity values, varying from 380 to 5320 m^2/d. The highest values may represent the transmissivity of the basal gravel unit of the drift that allows preferential flow (Severn Trent Water Authority 1978).

Six out of seven pumping tests on the Bromsgrove Sandstone Formation, analyzed by Ramingwong (1974) in the Droitwich-Kidderminster-Bromsgrove area of the Worcester basin, had a consistent mean bulk hydraulic conductivity of 0.3 m/d, with associated transmissivity values ranging between 30 and 400 m^2/d. The seventh, a test at Whitford [SO 935 706] had a value five times greater. This could be due to it being sited on the Hagley Fault, which has a high transmissivity (Black and Barker 1981).

Pumping test analyses of cored boreholes in the Tern area showed that transmissivity variations reflect the variations in estimated thickness of saturated aquifer. This suggests that the hydraulic conductivity of the Sherwood Sandstone Group is fairly constant with depth throughout the area (Severn River Authority 1972). Bulk hydraulic conductivities were calculated as 0.9 to 2.2 m/d. High hydraulic conductivity values were assumed to be due to deep and extensive weathering, which had presumably been developed during glaciation of the area, but which could also result from fracture flow.

Out-flow double packer testing and geophysical logging of the Bromsgrove Sandstone Formation is described by Ireland (1981). The Cow Lane observation hole, Dunhampton, Worcestershire [SO 848 660] was investigated to a depth of 145 m. Gamma logs showed low hydraulic conductivity clay-grade bands and caliper logs delineated fractured horizons. Packer testing, with the packers spaced 3.25 m apart, gave hydraulic conductivities which ranged between 0.24 and 2.52 m/d. The majority of the high hydraulic conductivity sections are fractured, and the low hydraulic conductivity sections are aquitards. The transmissivity profile, based on cumulative average hydraulic conductivity and cumulative aquifer thickness, shows a particularly marked increase at 110 m depth, the level of a significant fracture. A value of 117 m^2/d was obtained for the whole tested section. This compares well with the results of a pumping test at Dunhampton pumping station that gave a transmissivity of 125 m^2/d. A bulk hydraulic conductivity of 0.4 m/d is obtained when the transmissivity is divided by the length of packer tested section. This is comparable with the intergranular hydraulic conductivity of sandstones. Thus, although fracture flow is significant at some levels of the borehole, it does not dominate the transmissivity.

At a refuse tip at Seisdon [SO 843953], West Midlands, packer testing was carried out in order to look at permeability variations and leachate quality. It showed that leachate was being transferred into the sandstone via fractures (Fletcher, S. personal communication).

3.2.5 *Comparison of borehole transmissivities and core permeametry data*

Severn River Authority (1972) concluded, after comparing observations of cores, pumping tests and geophysical logging, that the Sherwood Sandstone Group in the Tern area is unlikely to be fractured on a large scale. The total flow is probably derived from a combination of intergranular and fracture flow. Worthington (1976) suggested field conductivity values of 0.3 to 2.5 m/d, which when compared to his geometric mean intergranular value of 0.3 m/d, also indicates a variable fracture contribution to transmissivity. Bulk hydraulic conductivities of 1.0, 2.1, 7.6, 2.0, 1.4 and 1.8 m/d were obtained for six boreholes in the Roden and North Shrewsbury area, which were generally in good agreement with core hydraulic conductivity data from the Tern area (Fletcher 1977). Nevertheless, a fracture flow component was attributed to Harcourt Mill, which had the anomalously high value of 7.6 m/d.

Ramingwong (1974) compared laboratory and field hydraulic conductivity values for two sites in the Droitwich syncline area, Worcestershire. At Whitford [SO 935 706], the field hydraulic conductivity of 1.4 m/d was over twice the core value of 0.66 m/d (geometric mean of 27 samples), indicating that fracture flow is significant and accounts for approximately half of the borehole yield. Conversely, at Ombersley [SO 836 629) the field value and lab value (geometric mean of 17 samples) were 0.39 m/d and 0.36 m/d respectively, implying that intergranular flow is locally dominant. Lovelock (1977) estimated from core samples an intergranular transmissivity of 268 m^2/d for the Kidderminster Formation at Littleton Colliery in Staffordshire. The pumping test derived total transmissivity was calculated as 2770 m^2/d, indicating that 90% of the flow was from fractures.

3.2.6 *Hydrograph data*

There appears to be little evidence for fracture flow from borehole hydrographs in this region.

3.2.7 *Geochemical studies*

There are very few geochemical studies pertinent to the affects of fracturing on the hydrogeology of the region, and the Environment Agency, Midlands Region have not investigated structural controls on water quality. Four boreholes at Stableford, near Bridgnorth [SO764981], West Midlands exhibit variable salinity. The boreholes are in a straight line, each 5 m apart. Geophysical conductivity logging confirmed that saline water enters fractures midway down Borehole 1, between depths of 60 and 140 m. It travels across the site and appears in whichever borehole is pumping. The water quality in the other boreholes improves when Borehole 1 is pumped. It has been inferred that inclined fractures offer the best explanation for the movement of saline waters between boreholes. Fletcher (1988) proposed that Borehole 1 should be grouted entirely in order to solve the water quality problems at the site. Another example is a forced gradient tracer test which was conducted at Heath House PWS, Shropshire by the British Geological Survey, which indicated transport rates between 5 and 40 m/d. These flow rates suggested intergranular rather than fracture flow in the sandstones at the site (Coleby, 1996).

3.2.8 *Models*

No large regional groundwater flow models have been undertaken in the Midlands Region of the Environment Agency. Knipe *et al.* (1993) modelled the Birmingham area as a single layer. The Bromsgrove, Wildmoor and Kidderminster Sandstone formations were treated as one unit, with a hydraulic conductivity of 1 to 1.5 m/d. This was multiplied by aquifer thickness to obtain transmissivity, the values of which ranged between 20 and 330 m^2/d. These are comparable to the seven pumping test derived transmissivities of the area, which varied between 65 and 370 m^2/d. Sensitivity analysis revealed that the model was far more reactive to river bed hydraulic conductivity and overall recharge than to transmissivity.

3.2.9 *Other evidence*

Fractures were encountered in a Pumping Station at Stourbridge [SO 893817] when a nested piezometer was grouted up. The level of grout stopped rising, despite considerable quantities being injected, once the fracture was encountered. However, when the grout had set overnight, the grouting process could continue with the level rising as expected until a new fracture was reached (Fletcher 1988). Sand pumping is rare, but has been observed at Blackstone [SO 79457432], near the River Severn, at Prestwood [SO 85878576], near Stourbridge (where subsidence has occurred), at Astley [SO 9033674], Kidderminster, and at the new Bromsberrow borehole development [SO 7372 3321]. At Helshaw Grange, during Phase 1 of the Shropshire Groundwater Investigation, a borehole 10 m from the abstraction borehole collapsed, and at Greenfields, water could be heard being sucked out of the observation borehole when the abstraction borehole 20 m away was pumped (Fletcher, S. personal communication).

3.3 Northwest

The north-west region, illustrated in Figure 1.1, includes the Permo-Triassic sandstones of Cheshire and South Lancashire, the Fylde and the Carlisle Basin. There is significant stratigraphic variation across this region (Figure 1.2) as a consequence of differences in the tectonic and sedimentary evolution of each of the basins, and the nature of fracturing also varies significantly across the region. Table 3.1 summarises the evidence for fracture controlled hydraulic properties in the north-west.

The Cheshire and West Lancashire Basins are *en echelon* basins bounded by syn-sedimentary extensional faults. The major structural features within the basins are large, generally north-south or north-west-south-east trending, normal faults with vertical throws of up to 300 m (e.g. Wem-Red Rock, Croxteth, Boundary, Eccleston and Warburton Faults). The Wirral peninsular is intensely faulted with major normal faults trending north-south and minor east-west trending faults. Growth faults within the West Lancashire Basin of the Fylde control significant intrabasinal changes in lithology (Brereton and Skinner 1974), however, superficial deposits obscure many of the faults in this area and little is known about them.

The Lake District massif dominates the structure of the sandstones of the Cumbrian coast, the Vale of Eden and the Carlisle Basin. The St Bees Sandstones exposed on the edge of the Manx Basin along the West Cumbrian coast dip gently towards the Irish Sea.

Probably the most significant and detailed investigation of the hydrogeology of a small area of Permo-Triassic sandstone - including an assessment of the nature and hydrogeological effects of fractures - yet carried out in the UK was undertaken at Sellafield in West Cumbria by UK Nirex. For this reason the results of the investigation are considered first, followed by other information for the rest of the region.

3.3.1 *The Nirex investigation of the Sherwood Sandstone Group at Sellafield*

Introduction

Between 1989 and 1997 UK Nirex Ltd carried out extensive investigations in the Sellafield area of West Cumbria to determine whether a site in the area could be suitable for a deep repository for the safe disposal of intermediate and certain low-level radioactive waste. As part of this work, the hydrogeology of the Sherwood Sandstone Group - which overlies the host rocks for the potential repository - was investigated. Since the Nirex study of the Sherwood Sandstone Group alone was one of the most detailed of any region of the aquifer in the country, the techniques used and the results obtained are summarised together in this section.

The following description and interpretation of the Sellafield work is summarised from Nirex (1997). The summary concentrates on investigations and results pertinent to the aquifer properties - and particularly the fracture hydrogeology - of the sandstones at depths of significance to the water industry (i.e. to around 200 m).

Geological setting

The Sherwood Sandstone Group in the Sellafield area was deposited on the margins of the East Irish Sea Basin and beneath the coastal plain area is up to 1300 m thick. The group thickens to the south-west and to the east is probably bounded by the Lake District Boundary Fault. The group is covered by variable thicknesses of glacial Drift onshore and is overlain by the Mercia Mudstone Group offshore. The Sherwood Sandstone Group is underlain by the Permian Brockram, St Bees Evaporite and St Bees Shale Formations, which in turn overlie the Carboniferous Limestone to the west and north. The Borrowdale Volcanic Group underlies much of the area (and was the host rock for the potential underground laboratory).

The Sherwood Sandstone Group at Sellafield has been subdivided into three formations. The St Bees Sandstone Formation at the base of the group is overlain by the Calder Sandstone Formation, which is in turn superseded by the Ormskirk Sandstone Formation.

The lower part of the St Bees Sandstone Formation is dominated by a sheetflood facies, which is characterised by frequent and laterally extensive mudstone sheets. The remainder of the formation consists of a stacked fluvial channel facies association, comprising mainly low sinuosity cross bedded fine to medium grained channel sandstones, but including mudstones. Mudstones are less common in the upper part of the formation .

The Calder Sandstone Formation at Sellafield is dominated by aeolian sandstones (with some fluvial sandstones) and has much less clay than the St Bees Sandstone. The Ormskirk Sandstone Formation was deposited entirely in an aeolian dune and interdune environment.

Diagenesis is likely to play a crucial role in the aquifer properties of the sandstone matrix. Eleven diagenetic episodes have been identified in the Permo-Triassic rocks at Sellafield, from syn-sedimentary near surface processes, via effects after burial through to recent uplift and the invasion of meteoric groundwaters. Each episode has caused the precipitation or dissolution of cements, or grain alteration and these have had corresponding effects on porosity and/or hydraulic conductivity.

The Sherwood Sandstone Group is disrupted by faults and other discontinuities that have influenced the properties of the aquifer. Each fault zone consists of one or more fault strands, each of which has an associated damage zone in which fracturing is greater than in the surrounding rock. The number of fault zones, and the number of fault strands within zones, decreases up the stratigraphic sequence. Fault movement was often syn-sedimentary so that formations may thicken across the faults and fault displacement tends to decrease up the sequence. Fault architecture is very heterogeneous; some parts of a fault zone may consist of fairly planar structures with well defined fault gouge and simple damage zones, but more commonly fault strands are splayed discontinuous anastomosing structures with overlapping damage zones.

The widths of fault damage zones vary, depending in part on the competence of the faulted strata, so that individual fractures may often be bed limited - terminating at bedding planes.

Away from fault zones the sandstones are pervasively jointed, forming blocks with a short side of generally less than one metre. At outcrop some joints have been observed to be stained, indicating the passage of water, but joint apertures are likely to decrease with depth, suggesting a concomitant decrease in hydraulic conductivity.

Bedding plane fractures are significant, particularly at shallow depths (less than 100 m below the ground) where stress relief due to erosional or glacial unloading may have initiated or enlarged fracture apertures and where carbonate solution has occured.

Investigation of the sandstones at Sellafield

The approach to the investigation of the Sherwood Sandstone Group at Sellafield was twofold. In one approach the geometrical properties of the material were examined and inferences were drawn about the likely hydraulic characteristics of the rock; in the other approach measurements at a range of scales were used to deduce hydraulic parameters. The two forms of investigation were then combined to produce a conceptual hydrogeological model of the sandstones.

The following summary of the investigations undertaken and the hydrogeological conclusions drawn from them focuses on the studies related to fractures, but it necessarily refers to matrix studies in view of the interaction between the modes of flow in the sandstones.

Stratigraphy, Sedimentology and Petrography

The sedimentary framework of the sandstones was studied using material from boreholes, from outcrop observations, from seismic data and from information held in reports. Borehole data were obtained from core logging and from a variety of geophysical logs (caliper, gamma, sonic, neutron, density and resistivity). Dipmeter and Formation Micro-Scanner log data were also used.

The data were interpreted to produce a model for the sedimentary architecture of the sandstones, which had implications for hydrogeological modelling.

For the St Bees Sandstone Formation the interpretation of the data suggested that the formation should not be regarded as a homogeneous sandstone-dominated succession with randomly distributed mudstones. Rather, the succession was seen to have a distinct and predictable order that could strongly influence flow. The data were interpreted to indicate several scales of variability for the St Bees Sandstone.

i) At the sub-metre scale (vertically) cross-bedding and similar depositional features dominate.

ii) At larger scales (up to the order of ten metres vertically) repeated channel sequences occur.

iii) At larger scales, up to hundreds of metres vertically, systematic variations in depositional facies and clay content are present.

In the lower parts of the sequence the sheet-like mudstones are likely to impart a significant hydraulic anisotropy, with some anisotropy in the planar bedded sandstones. The overlying channel sandstones are also likely to be anisotropic, with highest permeabilities oriented along channels. Permeabilities perpendicular to bedding may be reduced by mudstones and flow between channels may be reduced by sandstones rich in mudstone clasts that line channel bases.

Within the aeolian parts of the Ormskirk and Calder Sandstone formations, sedimentary low permeability features are likely to be uncommon in relation to the St Bees Sandstone Formation. However the Calder Sandstone Formation is now thought to be less homogeneous than had previously been assumed.

Core Analysis

Core analysis measurements were made on a total of 683 sandstone core plugs taken from 343 sampling points in twelve of the Nirex boreholes. Normally a vertical and one or two horizontal plugs were taken (the regional dip of the Sherwood Sandstone cored averages 21 degrees). Sampling intervals varied between 0.03 m and 224.95 m, with a geometric mean of 5.21 m. Resaturation porosity measurements were made on 291 plugs (generally one plug per sampling point). Gas permeability measurements were made on 652 plugs, generally comprising a vertical and a horizontal sample from each sampling point.

In addition, core analysis data were available from Environment Agency Boreholes in the region and a borehole drilled by British Nuclear Fuels.

Analysis of the data led to the following main conclusions:

i. Grain size appears to be a factor controlling matrix properties, but is not the only one.

ii. Modal values of porosity and permeability are greater for the aeolian Calder Sandstone Formation than for the fluvial St Bees Sandstone Formation.

iii. Porosities and permeabilities cover broad ranges at all depths, but maxima are higher above -300 m than below -600 m.

iv. The development of high porosity and permeability in the sandstones is controlled by a combination of sedimentological and diagenetic factors. Thus there is a primary sedimentological control (for example the distribution of clean well-sorted sandstone compared with more poorly sorted, argillaceous sandstones and mudstones). Then there is diagenetic control governed by the extent and timing of cementation and subsequent dissolution of both carbonate and evaporite cements. Cement dissolution is particularly well developed near the ground surface, suggesting that recent groundwater leaching is responsible for much of the secondary porosity. Prediction of the porosity characteristics in the deeper parts of the sequence is difficult at present.

Faults and discontinuities

A number of techniques were used at Sellafield to investigate faults and discontinuities. These included seismic interpretation, field mapping, core logging and borehole geophysical logs.

The study resulted in the following main conclusions of relevance to the hydrogeological characteristics of the sandstone aquifer:

i. The Sherwood Sandstone Group is cut by faults. Seismic data indicate that the frequency and displacements of the faults decrease in magnitude up the sequence.

ii. Some of the fault displacements are large enough for the Sherwood Sandstone Group to be juxtaposed against the Borrowdale Volcanic Group, causing potential hydraulic connection between the two units.

iii. The faults generally comprise one or more fault rock strands with associated damage zones. The fault strands tend to contain fine-grained clayey fault rocks whose permeability is considered to be lower than the background rock. The fault strands may therefore act as partial barriers to flow across the fault. Conversely the damage zones contain a higher frequency of discontinuities than the surrounding undamaged rock and may therefore form zones of enhanced permeability. Discontinuities within the fault damage zones tend to be truncated by bedding; therefore flow enhancement associated with the fault damage zones may be greater parallel to the fault strike than to its dip.

iv. Granulation seams with low permeability tend to be associated with faults, although their geometries and hydrogeological significance are poorly known.

v. The St Bees Sandstone contains both shallow and moderate to steeply-dipping discontinuities between fault zones. Most shallow-dipping discontinuities are related to bedding (bedding plane fractures) and are mainly concentrated within 120 m of the surface. The apertures of the shallow bedding plane fractures are thought to be relatively large (up to 10 mm) and may therefore be associated with significant transmissivity, as measured in boreholes.

vi. The moderate to steeply-dipping discontinuities are interpreted as joints, many of which are observed at outcrop to be partly or fully mineralised.

Diagenesis and fracture mineralisation

Detailed mineralogical and petrological investigations were undertaken on borehole core material using a variety of methods including optical petrography, scanning electron microscopy, electron microprobe analysis and microthermometric fluid inclusion analysis Supporting information was obtained from outcrop observations.

The work revealed that eleven diagenetic episodes have occurred in the sandstones and also nine episodes of fracture mineralisation. The study showed that much of the present day matrix porosity in the Sherwood Sandstone Group is secondary and was produced by the dissolution of pore-filling cements. This porosity is particularly well developed in near surface sandstones. Much of the present day fracture porosity may also have been produced by the dissolution of fracture filling materials. Both matrix cement dissolution and fracture mineralisation have occurred preferentially where groundwater flow was most active.

Porosity measurements from wireline logs

Porosity estimates can be derived from several of the wireline logs run in the Nirex boreholes at Sellafield. The three most important types of geophysically-derived porosity values in the Nirex programme are neutron porosity (measured with the neutron porosity tool), total intergranular porosity (derived from a combination of neutron porosity logs and information from other tools) and 'acoustic impedance porosity' (for a discussion of these see Nirex, 1997).

It was found that there was a close correspondence between wireline log derived porosity and core plug porosity measurements and as the wireline log datasets do not suffer from the problems of sampling relatively unconsolidated, or shaly material, the wireline data can be used to provide a comprehensive and consistent coverage of the Sellafield boreholes. Wireline porosities show a general reduction in depth and appear to support the existence of a near surface de-cemented unit. Porosities are significantly higher in the Calder and Ormskirk Sandstone formations than in the St Bees Sandstone Formation.

Wireline porosities tend to be greater in the fault damage zones in the sandstones.

Single borehole hydraulic tests

Three types of single borehole tests were performed in the Sherwood Sandstone Group (Sutton 1996):

i. Environmental Pressure Measurements (EPM). These were performed regularly at approximately 50 m intervals while the hole was being drilled. A single packer was used to isolate the bottom 50 m of the borehole, a drawdown was imposed on the test section and the recovery was monitored.

ii. Full Sector Tests (FST). These were gas-lift tests carried out over a large section of open borehole, using nitrogen gas injected through coiled tubing.

iii. Discrete Extraction Tests (DET). These were double-packer tests in which fluid was extracted from an isolated test zone which was usually targeted on a flowing feature.

Of the single borehole tests, the EPM test results are the most representative of the Sherwood Sandstone Group as a whole. EPM test results are available for 11 tests in the Calder Sandstone Formation and 78 tests in the St Bees Sandstone Formation; no tests were carried out in the Ormskirk Sandstone Formation. Twenty-four tests were carried out within 200 m of the ground surface, but only 11 were undertaken at depths shallower than 100 m.

Analysis of the EPM test results showed that the values of hydraulic conductivity are log-normally distributed with no apparent significant difference between Calder Sandstone Formation and St Bees Sandstone Formation values. Values of hydraulic conductivity within the upper 200 m are significantly greater than those below, with some evidence of a decrease with depth in the top 200 m. Hydraulic conductivity is weakly correlated with the number of flowing zones in the tested interval, and tends to be higher if there is a major fault in the interval.

Hydraulic conductivities derived from EPM tests are higher than core plug values from the same part of the Sherwood Sandstone Group - suggesting that fractures contribute to flow to boreholes under test conditions.

Pumping Tests

A major testing programme was carried out in one Nirex borehole (RCF3) included the testing of two intervals (-141 m to -296 m aOD and -296 m to -345 m aOD) in the Sherwood Sandstone Group by constant rate abstraction, with responses monitored in over 20 monitoring zones in nearby boreholes. Nirex also tested several other boreholes in the area. In addition data were available from a number of tests carried out by the Environment Agency (then the National Rivers Authority) in the 1980's.

Analyses of the Borehole RCF3 Sherwood Sandstone Group pumping test results indicated mainly 2-D radial flow, with some partly effective lateral barriers and significant anisotropy. There was significant attenuation between the St Bees Sandstone Formation zones tested and the underlying sheetflood facies. Both pumping tests produced responses in the Borrowdale Volcanic Group where the two formations are juxtaposed by a fault.

Near-surface pumping tests in other boreholes in the St Bees Sandstone suggest much higher hydraulic conductivity values than were obtained for the St Bees Sandstone Formation tested at depth in Borehole RCF3. These near surface results were higher than were indicated by core plugs and similar to, or higher than, those suggested by EPM tests. It was concluded that fractures, particularly those parallel to bedding, contribute significantly to the increase in transmissivity near to the surface. This conclusion was supported by rapid, confined-type responses being seen over distances of up to 1.2 km, but not consistently over the areas. These responses may apparently cross faults, indicating a complex interaction between bedding plane features and faults at shallow depths. Modelling of Environment Agency tests suggests that the bedding plane fractures may have horizontal dimensions of the order of a few hundred metres.

A basal permeable layer of the Drift was also seen to affect responses to pumping in one test.

Flow Zone Characterisation

Flow zones were investigated by using logs run in boreholes during single hole hydraulic tests. Inflows were shown on temperature, conductivity and occasionally flowmeter logs. For the Sherwood Sandstone Group it was seen that EPM intervals containing at least one flow zone were significantly more permeable (around an order of magnitude) than those containing no such features. Also intervals with two and four flow zones tended to be more permeable than those with only one.

A second line of investigation was the examination of core to identify features that have the potential to allow flow (Potential Flowing Features or PFFs) and to identify the geological characteristics of the known Flow Zones. PFFs were identified on the basis of the presence of natural connected porosity on the core scale and an association with certain mineralogical and petrological characteristics such as evidence of geologically recent mineral dissolution or well developed crystal forms that have deen dated as being of Quaternary age.

Six discrete types of flowing features were categorised by comparing Flow Zones and PFFs identified in equivalent core. These are; A) permeable matrix, B) porous fault planes, C) undifferentiated fracures, D) steep dilational fractures, E) stress-relief bedding plane fractures and F) dissolution of fracture minerals.

Studies of Flow Zone and PFFs data led to the following main conclusions:

i. There is a very close association of specific late mineralisation episodes (classed as ME8 and ME9) with PFFs and with fracture-controlled Flow Zones in all the boreholes examined.

ii. Many of the Flow Zones identified in the Calder and St Bees Sandstone formations correlate very closely with one or more Potential Flowing Features; however many do not.

iii. Of the six types of potential Flowing Features identified it was considered that type 'A' (matrix) features provided a major component of flow in the Sherwood Sandstone Group. However type 'E' (bedding plane fractures) were thought to possibly be more important in providing flow to boreholes at shallow depths, and might enhance regional groundwater flow under natural gradients to a small degree. Although type 'E' features may have large apertures near to boreholes they were not considered to be well connected over distances greater than several hundred metres. Type 'F' features (dissolution of carbonate vein infills) were considered to be potentially important at shallow depths.

iv. Studies of the degree of association of flow in the St Bees Sandstone Formation with fractures suggested that fracture flow was most significant within 200 m of the ground surface.

Summary - flow in the near surface Sherwood Sandstone Group

From the studies outlined above it was concluded that groundwater flow in the Sherwood Sandstone Group under natural and forced gradients takes place through both the matrix and through fractures. The relative significance of each mode of flow varies with depth and with the scale of observation. On a regional scale (>1 km) fractures are considered to be poorly connected and matrix flow dominates. At the borehole scale fracture flow may dominate (although many flowing zones are associated with the matrix). Near the surface bedding plane fractures are dominant, whereas at greater depths fractures are more likely to be steeply inclined and associated with faults .

The work undertaken by Nirex suggests that the upper part of the St Bees Sandstone Formation (within around 200 m of the surface in the Potential Repository Zone) has a higher hydraulic conductivity than the underlying material. The Calder Sandstone Formation appears (on the basis of a pumping test and core measurements) to have a significantly higher hydraulic conductivity than the St Bees Sandstone.

Conclusions relevant to the Scoping study

There are several results of the Nirex investigations at Sellafield which are especially significant for the fracture hydrogeology scoping study:

i. Fractures are identified as important routes for flow at depths of interest for water supply.

ii. Such fractures are commonly bedding-plane features.

iii. The extent of the fractures is unlikely to be greater than a few hundred metres.

iv. Fault structures are surmised to comprise low permeability cores and high permeability damage zones.

3.3.2 *Northwest region - general*

Cumbria

In general, occasional boreholes show the hydraulic effects of fracturing in the north-west with anomalously high productivity in areas where yields are generally poor. An example is the unusually high yielding borehole at Ousby Moor [NY 5310]. The St Bees Sandstone has generally low permeability except in faulted areas, such as Scales [NY 1836 4605]. At Egremont, West Cumbria, only one out of six boreholes yielded a significant flow. Hydrofracturing was tried at Holmwrangle [NY 518 492] to improve the yield of the poor holes there. At Schneider Road [SD196707] and Thorncliffe Road [SD 196709], Barrow in Furness, some boreholes have reasonable yields, others do not. Borehole yields depend to a very large extent on fracture interception (Campbell, J. (Bechtel Water Technology Ltd), personal communication). Yields are not significantly increased by drilling below 200 m, presumably due to the closing of fractures with depth (Peacock, A. J. personal communication).

In contrast, flow in the Penrith Sandstone Formation is more intergranular in nature, with high porosity and low hydraulic gradients, and stepping of the water table is rare. Bedding plane fractures are a feature of the Penrith Sandstone Formation but there is little evidence that it becomes less permeable with depth as overburden causes fractures to close.

Fylde

Variations in transmissivity values in the Fylde arise both from fracturing and from the sandstones being in hydraulic contact with high yielding thick sand bodies in the drift, which are often in turn connected to rivers. Marl layers, sharp folding and faulting can give rise to compartmentalisation.

Cheshire and South Lancashire

The degree of fracture flow varies between lithologies. Fractures seen on CCTV logs are largest, most extensive, and stay open most in the Chester Pebble Beds Formation. A good flow can be obtained from just 1 or 2 fractures. Fractures in the Wilmslow Sandstone Formation are smaller, less extensive, and have lower flows. Sand pumping and cavity development is most significant in this formation, because of its low cementation (Campbell, J. personal communication). Lack of fractures at Newton Hollow No 2 and 3 boreholes explain their low hydraulic conductivity (c. 0.2 m/d). The Whitbread Ltd [SD5826 2968] and Courtaulds [SD 380988] boreholes are now known to be located on a fault and influenced by faulting in the south east.

3.3.3 *Regionally or locally hydraulically significant faults*

Cheshire and South Lancashire

Examples of reduced permeability faults are the Croxteth Fault, North Merseyside and the Winwick Fault, Lower Mersey Basin which cause Carboniferous strata to be up-thrown against Permo-Triassic deposits and inliers of Carboniferous deposits to outcrop. They can only be modelled if their assigned transmissivities are significantly lower than the regional values (University of Birmingham 1981 and 1984).

In East Cheshire, an ICI borehole at [SJ 972760] is located in a fault controlled trough. The water has been mined from it by pumping. Upconed saline groundwater is present at Trafford Park [SJ 780980].

The Widnes Depression, east of the Croxteth Fault is a structurally controlled elongated depression. Water from it is used for both industrial and public supply purposes, and water levels have declined to below sea level. It is mentioned in the Mersey and Weaver River Authority First Periodical Survey (1969).

Basins below the Fylde Plain have recently been remapped by BGS. The horst and graben structure accounts for the surprisingly sluggish response in the south-east of the aquifer to abstraction elsewhere.
Extensive faulting results in complex geology in the east Manchester area. Faults may facilitate the circulation of water by the displacement of the minor marl bands (Taylor 1957). Faults east of the Pendleton Fault have elevated the Manchester Marl aquitard into a series of north-west-south-east trending barriers to groundwater flow, dipping to the south-west. Where the Manchester Marl outcrops, for example along the West Manchester Fault, it divides the Permo-Triassic sediments into isolated aquifer blocks. Most blocks taper and thin northwards. Thinning of the Permo-Triassic Sandstones on the upthrown faces of the faulted blocks produces regional hydraulic anisotropy (Pitman 1981).

Effect of infill

The nature of the fault zones is difficult to predict and both permeable and impermeable faults occur. Some faults are filled with loose, porous debris. Others have impermeable clay infill. The Roaring Meg Fault in the Lower Mersey Basin, does not interrupt sandstone continuity but can only be successfully modelled if the transmissivity across it is reduced to 5% of the regional value. The fault delineates a transition between water chemistry types which also suggests that it is of low hydraulic conductivity (University of Birmingham 1981).
Resistivity data in the region of Hale [SJ 47 81] indicate that the saline interface there has been disturbed by a low permeability fault zone (University of Birmingham 1981).

Hard, altered, reduced porosity zones surrounding some faults have been recorded. Moore (1902) measured hydraulic conductivity variations across a fault at West Kirby [SJ 21 86] where Triassic sediments were discoloured within 1 m of a metre wide fault zone. A 40% fall in porosity occurred near the fault; it was suggested that this was due to rock compression and the presence of rock flour (University of Birmingham 1981). Where boreholes have encountered faults, the cores are frequently broken and records show fault zones extending up to some 40 m. At Bewsey [SJ 592 894] and Halewood [SJ 464 838] calcite cementation occurs in the faulted zone. At Bewsey minor clay gouge is also present. Mining subsidence has caused recent local movement. At Holcroft Lane Observation Borehole [SJ 6857 9370] some of the fractured material has been recemented (University of Birmingham 1981).

Aquifer boundary - Ormskirk

An asymmetrical cone of depression resulting from six years of abstraction from a supply borehole at Bickerstaffe Pumping Station, 3 km south of Ormskirk [SD 420 035] is described by Allen (1969). It is 2 km east of the Boundary Fault, which separates Coal Measures upthrust to the east from the Sherwood Sandstone Group to the west. Observation boreholes at right-angles to the abstraction well indicate a cone of depression elongated parallel to the fault, with a greater drawdown adjacent to it. Interpretation of drawdowns, at the various observation wells, would yield misleading aquifer parameters if the effect of the barrier boundary nature of the fault was not taken into account.

Barrier fault - Sandon Dock

Campbell (1987a) describes how faulting affects the tidal response of observation borehole hydrographs, and how it can influence pumping test results. The presence of a low hydraulic conductivity fault at Sandon Dock, Liverpool [SJ 335 925] is deduced from borehole hydrographs and is consistent with borehole lithological data. The tidal efficiency (change in borehole water level per change of tidal level) of three boreholes (numbers 321, 325 and 327) to the inland side of the fault is 5%, whereas that of the nearby three boreholes (numbers 326, 328 and 331), on the fault's seaward side is 30%. Thus the fault appears to restrict flow across it.

Analysis of a pumping test carried out on inland borehole 325, using observation boreholes 321 and 327 adjacent to the fault, indicated aquifer properties that overestimated the drawdown at borehole 325. The modelled storage was increased from 3×10^{-3} to 8×10^{-3} to account for this. A step test on borehole 326, produced little drawdown in observation boreholes 321, 325, and 327 on the opposite side of the fault. The water level in borehole 325 actually rose because the tidal rise exceeded the drawdown. A 7 day pumping test on seaward holes 326, 328, and 331 produced only 0.9 m drawdown at borehole 327, inland of the fault. A drawdown of 5 m would have been expected if the fault barrier had been absent.

North-west

High transmissivity fault - Scales

At Scales Demesne, West Cumbria, a borehole [NY 1836 8605] on the Crummock Fault is highly productive. It penetrates the drift and St Bees Sandstone Formation, and yields 7 000 m^3/d with a 20 m drawdown. Another borehole [NY 1809 4605], located 300 m to the north-west but off the fault yielded just 500 m^3/d with a 70 m drawdown, and was abandoned. Two nearby boreholes at Low Scales [NY 1870 4613 and NY 1873 4615] have moderate yields of 2 000-3000 m^3/d. Again, they are not located on the fault linearity. The variability of the yield can be explained by fracturing. The Crummock Fault is highly transmissive; pumping from the Scales Demesne abstraction borehole rapidly affects springs in Bromfield, 1 km away. Most of the aquifer is poor yielding, with a transmissivity of 50 m^2/d or less (Peacock, A. J. personal communication).

The area is overlain by 45 m of drift, the top 25 m of which is boulder clay. Sandy drift may be enhanced along the fault and could act as a highly transmissive layer, The Bromfield Springs, Crummock Beck and Langrigg Beck are all affected by pumping. Together they contribute all of the abstracted water. More water can be obtained from long duration - low discharge rate pumping than by pumping at higher rates for shorter times, as for instance during pumping tests. Pumping at Scales also influences shallow wells at Crookdale Hall on the sandstone outcrop further up the fault. Their water level is 40 m higher than that at Scales, and they respond with a 20 cm fall in level. The hydraulic influence of the Crummock Fault, could project north-westwards too, affecting drift beyond the aquifer. Thus wetlands beyond the aquifer could be affected by pumping from it (Peacock, A. J. personal communication).

Faulted river connections - Calder Valley

Faulting is likely in the Calder Valley, West Cumbria. At the BNFL site, there are thought to be fracture connections between the boreholes and the river. In the upper Calder valley there is a high degree of connection between the St Bees Sandstone Formation (where it outcrops inland) and the river. The groundwater flow to the river can be seen in water levels near the top of the Sherwood Sandstone Group, but is not seen in deeper water levels, illustrating the anisotropic nature of the aquifer. If groundwater is pumped for river augmentation then the initial net gain to the river flow declines with time. It is thought that water enters the aquifer where fault and fracture zones intersect the river bed (Ireland and Avery 1976). A North

West Water Authority investigation around Egremont identified induced effects on small rivers during pumping tests on investigation boreholes (Ingram, J. A. personal communication).

3.3.4 *Geophysical logging*

Environment Agency data

Paper records of conductivity, temperature and gamma logs exist prior to 1984. From 1984 to 1990 Robertson Geolog 1000 files exist. There are 200 - 300 in total[1]. Logs run include sonic, caliper, conductivity, gamma, resistivity and differential temperature. Some dual laterologs (focused resistivity) have been run to examine the saline interface. Many logs show the influence of fractures. Peaks on sonic logs often coincide with caliper log cavities. Conductivity profiles show steps from the upward progression of saline water. Significant logs have been written up in reports. No data have been collected since 1990.

North West Water data

CCTV logs are held by North West Water plc. No geophysical logging data are held by Bechtel Water Technology Ltd (formerly North West Water Engineering).

Cliburn

Fluid logging at Cliburn indicated numerous fractures mainly above 30 mbgl. Closed circuit TV (CCTV) showed a major fracture at 29.3 m (over 1 cm wide). Another major fracture near the base of the hole was indicated by heat pulse flow measurements and was seen on CCTV, but was not picked up by the temperature and conductivity logs. Flow logging suggested that water was entering the borehole near the water table (with a major contribution from the fracture at 29.3 m) travelling down the borehole and leaving via a fracture at 58.5 mbgl. CCTV indicated suspended particles following this path down the borehole. The many small fractures between the water table and the fracture at 29.3 m did not appear to contribute much water when the borehole was logged (Price *et al.* 1982).

This evidence suggests that in some boreholes much of the water is derived from only a small number of active fractures whilst many fractures have little or no contribution to flow. This also indicates incipient vertical hydraulic gradients maintained within the Penrith Sandstone Formation: probably on account of variable cementation and associated anisotropy. This in turn suggests that vertical fractures (or jointing) are not important in transmitting water, fractures detected within the borehole being mainly along horizontal bedding planes.

Cheshire and South Lancashire

Borehole Closed Circuit Television (CCTV) logging indicates that fractures are preferentially developed in the softer, less well cemented sandstones, such as the Wilmslow Sandstone Formation. For example, in the Padgate [SJ 629 900] and Bewsey [SJ 592 894] boreholes they occur at an average of ten per 10 m. In the more cemented Chester Pebble Beds Formation there is an average of two to three bedding plane fractures per 10 m of section down to a depth of 150 m at Croft [SJ 644 945]. Below this, the average is one fracture per 50 m. In the underlying Collyhurst Sandstone Formation, vertical joints are common but are frequently recemented with silica.

It is, however, difficult to tell the difference between original "real" fractures and "apparent" secondary ones, which have been created by the borehole drilling, development and abstraction. These man-made fractures develop fastest in easily eroded formations and can impart the appearance of a high fracture density, but these apparent fractures are not of regional significance because they are borehole scale phenomena.

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[1] These are held as graphical printouts, as processed number summaries at metre to 5 m intervals, as archive files from Wellog on 5.25" floppy discs and as the original raw data files.

Geophysical borehole logs and CCTV at Padgate [SJ 629 900] confirm that the zones with higher packer test hydraulic conductivity coincide with fractures. The lateral extent of both horizontal and vertical fractures is poorly known however. At the Kenyon Junction borehole site [SJ 648 965] fractures extend between boreholes 30 m apart, while at Padgate fracture patterns can be correlated in boreholes 90 m apart. The presence of fractures does not necessarily indicate higher hydraulic conductivity. In certain regions hydraulic conductivities are low despite fracturing, for example at a depth of 120 m in the Padgate borehole. Permeable zones are more frequent in its upper 90 m, indicating that a greater proportion of the water flows in this region (University of Birmingham 1981).

3.3.5 *Hydraulic testing*

Groundwater flow in the Calder Sandstone Formation and the St Bees Sandstone Formations is driven by recharge in areas of higher topography inland to the east (Nirex 1993). Groundwater flow occurs mainly in fractures, at least on a local scale, and the aquifer has a low storage coefficient 10^{-4} to 10^{-5}. Reasonable yields are only obtained when boreholes intersect fractures.

In the upper Calder valley there is a high degree of connection between the St Bees Sandstone Formation (where it outcrops inland) and the river. The groundwater flow to the river can be seen in water levels near the top of the Sherwood Sandstone Group, but is not seen in deeper water levels, illustrating the anisotropic nature of the aquifer. If groundwater is pumped for river augmentation then the initial net gain to the river flow declines with time. It is thought that water enters the aquifer where fault and fracture zones intersect the river bed (Ireland and Avery 1976). A North West Water Authority investigation around Egremont identified induced effects on small rivers during pumping tests on investigation boreholes (Ingram, J. A. personal communication).

In the Furness region the Bowater Scott Works Borehole [SD 199 725] was cored from 44 m to 166 m through St Bees Sandstone Formation which was fractured near its top but appeared to have little permeability at depth (Allen *et al.* 1997).

The Leece borehole in the Furness region [SD 241 685] had an artesian head when unpumped (1976) but had a drawdown of 59 m for a discharge of 650 m^3/d (specific capacity 11 $m^3/d/m$) indicating a low transmissivity (the borehole is considered to be in a faulted block where the aquifer is thin; Ingram J. A. personal communication). The high water level in this area is indicative of low regional permeability in relatively thin sandstones, with low fracture connection, which allows high heads to develop.

Packer tests

Packer tests- Cliburn (Cumbria)

At the Cliburn research borehole [NY 585 260], south of Penrith, in the Eden Valley packer tests were carried out at various intervals. There was evidence for considerable anisotropy of the sediments, which suggests the lack of permeable vertical fracturing in the area (Price *et al.* 1982). Packer and laboratory permeability measurements show good agreement in most of the borehole, indicating that most of the small fractures in the borehole wall are not permeable. The exceptions are two intervals with flowing fractures (see Section 3.3.4) which together contribute most of the transmissivity of the borehole.

Packer tests were carried out at various intervals in the Cliburn research borehole. Two packers isolated each interval (except that at the base of the borehole). There was evidence for considerable anisotropy of the sediments ($K_h>K_v$), which, when corrected for, lead to an increase in the estimated horizontal permeability (Price *et al.* 1982). This anisotropy is evidence for the lack of permeable vertical fracturing in the area.

From a total pumping test transmissivity of 1350 m^2/d between the water table and 60 mbgl, 85% appears to come from zones containing two main fractures, leaving a transmissivity of only around 200 m^2/d attributable to the essentially unfractured zones. This was found to agree well with estimates from laboratory measurements on core samples. It is likely that minor fracturing near the top of the borehole increases the injection transmissivity slightly above the laboratory intergranular values. These results suggest that the Penrith Sandstone Formation at Cliburn has limited hydraulic conductivity that is attributable to matrix flow over much of its thickness, and zones of very high local flow when fractures are present.

Packer tests - West Cheshire

Packer tests were carried out in the Lower Mersey Basin and in West Cheshire for the Saline Groundwater Investigations. Transmissivities were calculated for each test zone using empirical formulae. These were divided by the length of the test zone in order to obtain average bulk hydraulic conductivities, which could then be compared with core data. The cumulative transmissivities compare well with pumping-test transmissivities when turbulent flow is minimised (Ingram *et. al.* 1981a and 1981b).

Four sites were investigated in West Cheshire: Organsdale [SJ 5507 6830], Priors Heyes [SJ 5130 6645], Burton [SJ 5056 6464] and Stanlow [SJ 4309 7620]. Significant hydraulic conductivity increases can be attributed to fracture flow. Campbell (1986) summarised the results thus:

i. Hydraulic conductivity values obtained in fractured sections are generally much higher than in the unfractured sections.

ii. A zone of high hydraulic conductivity exists in the top part of the aquifer where fractures are common.

iii. Underlying this is a low hydraulic conductivity zone (generally less than 1 m/d) where intergranular flow predominates and fractures are rare.

Packer tests - Lower Mersey basin

In the Lower Mersey Basin, packer testing was conducted at Padgate [SJ 629 900], Kenyon Junction [SJ 648 965], and Halewood [SJ 464 838]. Profiles of average hydraulic conductivity suggest that there are a number of zones of unusually high hydraulic conductivity. At Halewood, approximately 80% of the flow was attributed to fractures and the Bold Formation was found to have a low hydraulic conductivity where it is not fractured (Walthall and Ingram 1981). Similarly, at Padgate 85% of the transmissivity of the 170 m of the Chester Pebble Beds Formation penetrated was attributed to sub-horizontal fracture flow (Walthall and Ingram 1982). Different results were obtained over the same 80 to 90 m depth interval at two observation boreholes only 30 m apart, indicating that zones of higher hydraulic conductivity can be very localised (University of Birmingham 1981)

Pumping tests

Cumbria

At relatively shallow depths (of the order of 100 m), both the Triassic Sherwood Sandstone Group (the St Bees Sandstone Formation) and the Permian Penrith Sandstone Formation are good aquifers. Typical values for field transmissivities are 100 to 300 m^2/d but values can be much higher reaching 1000s m^2/d (Lovelock 1977). Generally the transmissivity obtained from pumping tests in the West Cumbria area is of the order of hundreds of metres squared per day, and from available pumping test data the geometric mean of transmissivity for all the aquifers of the whole north-west region is 240 m^2/d (Allen *et al.* 1997). The large difference between the intergranular and field transmissivities reflects the extent that fractures control the rate of flow through the aquifers (at least on a local scale) (Allen *et al.* 1997).

There are very limited pumping test data for the St Bees Sandstone Formation in the Vale of Eden. Transmissivity values were in the range 167 to 276 m^2/d (Ingram, J. A. personal communication). Skirwith observation borehole [NY 613 325] had an airlift yield of around 200 m^3/d, and an observation borehole at

Ousby Moor [NY 596 358], drilled through a fault zone had a higher artesian flow of 470 m^3/d. Thus it may appear that some fault zones in this region are permeable, however the sustainability of these yields is unknown (Ingram 1978).

In the west Cumbria area the transmissivity depends on the degree of fault and fracture intersection in the boreholes; the highest yields are obtained for boreholes located in a fault zone. Groundwater flow occurs predominantly in fractures, the degree of fracture intersection in a borehole determining the local transmissivity. The aquifer shows signs of being fairly anisotropic, and there is local connection between surface water and the aquifer. Transmissivities range from less than 10 to over 100 m^2/d (Allen *et al.* 1997) with a geometric mean of 160 m^2/d. In the Brow Top region in the Calder Valley [NY 03 06], transmissivity values are variable, transmissivities, (on pumping wells without observation wells), are in the range 65 to 370 m^2/d with estimated confined storage (Ireland and Avery 1976).

Kirby Thore

Silicified microfaults with millimetre to centimetre displacements are present in the Penrith Sandstone at, Kirby Thore, Eden Valley. They cause anisotropic responses to pumping from the British Gypsum boreholes, [NY 643 260] where a distant borehole was more affected by pumping than a close one.

Cliburn [NY 585 260]

At Cliburn, south of Penrith, transmissivities of around 1900 m^2/d were found; much greater than those calculated from matrix permeability (128 m^2/d), indicating preferential flow. This preferential flow could come from either more permeable horizons or from fractures. Sub-horizontal bedding plane fractures are likely to provide most of this flow, amounting to about 90% of flow to the borehole (Ingram 1978). A more detailed analysis of the permeability distribution in a research borehole in the Penrith Sandstone Formation at Cliburn (Price *et al.* 1982), indicated that, although probably of limited extent, two fractures contributed 85% of the total transmissivity, intergranular transmissivity being only 175 to 200 m^2/d.

Holmwrangle [NY 518 492]

Pump testing at Holmwrangle Fish Hatchery gave a transmissivity of around 60 m^2/d, with much of the water coming from the River Eden nearby. There is a steep hydraulic gradient in the aquifer near this borehole, indicative of low permeability. High hydraulic gradients and artesian conditions, indicate little natural through flow of water, typical of poorly permeable areas. Boreholes that have a higher transmissivity do not have initially artesian conditions and are located in areas with fairly flat hydraulic gradients.

Fairhill [NY 512 314]

At Fairhill, near Penrith, radial flow modelling of pumping tests suggested very high values of permeability, implying fracture flow in the Penrith Sandstone Formation (Campbell 1992).

Cheshire and South Lancashire

Ashton

A fault at Ashton [SJ 505 689], West Cheshire was identified during analysis of extensive pump testing carried out in May 1970. The boreholes penetrate the drift and Chester Pebble Beds Formation. Drawdowns were recorded at observation holes 1, 2, 3 and 4, situated 180 m south, 140 m east, 170 m north-west and 640 m north-west of the main production borehole respectively. The array of observation boreholes allowed consideration of lateral variations of transmissivity. Values calculated for observation boreholes 1 to 3 were reasonably consistent. However, minimal effects of pumping at Mouldsworth [SJ 503 704] were observed at observation borehole 4 compared with the other Ashton boreholes. This is thought to be due to the presence of an impermeable fault between Mouldsworth and observation borehole 4, which would be consistent with the inferred geology. Correlation of geological core logs with gamma logging across the site indicated 30 m of displacement between observation boreholes 3 and 4 (Mersey and Weaver River Authority 1970).

Lightshaw

Step tests carried out on the eight Lightshaw boreholes, Lower Mersey Basin revealed a large range of transmissivity values, 83 to 1370 m^2/d, reflecting the varying degree of fracturing at the sites, rather than variations in the nature of the sandstones. Associated bulk hydraulic conductivities range from 1.2 to 16 m/d. Regional computer modelling of the aquifer suggests an overall permeability of 1.5 m/d, and the average intergranular permeability of the sandstones is 0.5 m/d (Campbell 1987b).

3.3.6 *Hydrograph and piezometry data*

Hydrographs in the Fylde and Mersey Basin are more influenced by seasonal abstraction than by recharge. Hydrographs in West Cumbria show the response to recharge better. There is a larger water level fluctuation (up to 15 m) towards the hill tops than in the more permeable valleys. The system has low storage and steep topography. Hydrographs from Furness Abbey, Cumbria are particularly flashy, with a larger range than others.

Piezometric Maps at one to ten year intervals have been produced for the North West Region of the Environment Agency. There is a marked variation in groundwater heads in Barrow in Furness peninsular, where the Permo-Triassic Sandstones are confined by the Mercia Mudstone Group. The correlation between observation boreholes' hydrographs and structural blocks can show whether adjacent fault bounded blocks are acting as individual hydraulic units. Discrepancies between blocks may arise from alternate ones being recharge and discharge areas (Birmingham University 1981) (Thewsey, M. personal communication).

Around Tattenhall PWS, Chester [SJ 480 580] there is a perched block of aquifer, which initially had high water levels. The hydrographs within the block show different responses to those of neighbouring blocks (Simpson and Partners 1996). On the Wirral Peninsular, there are marked head contrasts between the centre of the peninsular and along the Mersey Estuary, where water levels are below sea level. This indicates structural control. Remapping of the Wirral is currently being undertaken.

Compartmentalisation within the aquifers affects the nature of their water level recovery. Recoveries occur after drought and cessation of pumping from major boreholes or mine workings. Fractures facilitate mine water rebound. Fissure flow aquifers recover faster than intergranular ones, because the latter need a much larger head for rehydration. Dramatically fast recoveries have been observed in the Alt Valley, Liverpool [SJ 380990], at Courtaulds [SJ 380988] and at Winwick (Thewsey, M. personal communication).

Seven to eight metre head differences occur over short distances in the vicinity of the Bilsborough Fault, Preston (Ingram, J. personal communication). At Sandon Dock, water levels in boreholes on either side of a postulated fault respond differently to the tide (Campbell 1987a). There is a 3 m head difference across the minor Downall Green Fault at Sankey Valley, Newton le Willows [SJ 574946]. Water levels are 5.57 m below ground level on one side, and 8.87 m bgl on the other side. Head contrasts exist between three boreholes at the Cavaghner and Grey Co., Carlisle, which also suggest the influence of faults.

Case Study: Fiddlers Ferry

Both head differences and chemical differences occur at the Fiddlers Ferry Power Station site, Merseyside [SJ 58]. A low permeability fault barrier with a downthrow of 88 m to the east divides the aquifer in the vicinity of the site into two sections. Four of the site boreholes penetrate the eastern section, and one penetrates the western section. The water level, water quality and aquifer permeability in the two sections are different and almost independent of each other.

The western section has water levels 18 m below sea level, and a water quality that indicates minor contamination with saline water. The permeability is high, and dominantly fissure controlled. The eastern aquifer section has water levels just above sea level, and water quality indicative of a long residence time in the aquifer. The permeability is lower as there are fewer fissures. It appears that either the eastern area was not affected by previous development in the Warrington/Widnes districts, or that following recent decreases in abstraction, recovery has returned water levels to their pre-development levels (Groundwater Development Consultants Ltd 1988).

3.3.7 *Geochemical studies*

Saline water pumped from the Croft borehole [SJ 644 944], near Warrington, may be connected with the saline Warburton Fault. Saline springs were intercepted when the ship canal was cut over the Warburton fault. At Croft, there are two 200 m deep abstraction boreholes and a 320 m observation borehole at nearby High Croft Farm. During pumping the observation borehole has a saline interface at 160 m below ground level, which sinks below the base of the borehole when pumping stops. A fault connection near the base of the borehole is thought to act as a conduit for saline water from depth (Thewsey, M. and Campbell, J. personal communication). Saline water was used as a natural tracer for the saline study in the Lower Mersey Basin and North Merseyside (University of Birmingham 1981, 1984). Where fracture flow is significant, the saline interface observed in boreholes is sharp. Where intergranular flow predominates, the interface is diffuse. Water chemistry differences have been observed across the Roaring Meg Fault, Lower Mersey Basin (University of Birmingham 1981) and the fault at Fiddlers Ferry power station (Groundwater Development Consultants 1988). Tracers were injected into a piezometer at Haskayne, Lancashire [SD 3508] (Green 1994, Betts 1996) and monitored in a pumped borehole 5 m away. The observed breakthrough curves were interpreted as being the summation of three individual pulses of tracer: two representing the transport of tracer along rapid pathways through fractures, and a slower pathway representing the majority (66%) of flow through the sandstone matrix.

3.3.8 *Models*

Lower Mersey basin and North Merseyside

When the North Merseyside and Lower Mersey basin areas were modelled for the Saline Intrusion Investigation, it was assumed that the general fracture system is regular on a regional scale, despite the fracture distribution, size, frequency and extent appearing to be fairly random, at least on a local basis (University of Birmingham 1981 and 1984). The aquifer was modelled with two layers, in order to reflect the upper part of the aquifer contributing a greater proportion of the transmissivity. The upper layer was given a hydraulic conductivity of 1.7 m/d, and the lower one a hydraulic conductivity of 0.17 m/d. The boundary between the two layers was put at 200 m below Ordnance Datum, in the absence of conclusive information that it should be a function of glacial topography or present topography. Minor adjustments were made in the vicinity of faults. It was predicted that this universal approach may cause errors of up to 2 m in modelled groundwater head values.

Exceptions to the uniform hydraulic conductivity distribution were made adjacent to the Roaring Meg and Winwick faults. The 1979 groundwater heads could only be modelled accurately if the transmissivity across them was reduced to 5% of the regional value. Other faults may also be impermeable but, due to their position and trend, they have little influence on the 1979 flow regime and therefore do not need to be modelled with low transmissivities.

Fylde

Mott MacDonald have recently remodelled the Fylde region. In the model faults were modelled as hydraulic barriers. Horsts and grabens were included to account for some parts of the aquifer responding sluggishly to abstraction elsewhere. Good simulations of observed piezometry over a 20 year period were obtained by using transmissivities predominantly in the range of 500 to 2000 m^2/d (corresponding to hydraulic conductivity values of upto 10 m/d). The aquifer was modelled as two-layer system, reflecting the presence of relatively persistent low permeability marl layers within the sequence. This was necessary to simulate the observed piezometry across the Fylde aquifer over the last 20 years of operation of the Lancashire Conjunctive Use Scheme (LCUS). The presence of sands with high storage and permeability in hydraulic continuity with rivers may also account for the apparently high sandstone transmissivity values (Seymour, K. personal communication).

Cumbria

A number of models were used by UK Nirex to investigate groundwater flow in the Sellafield region of West Cumbria. The most relevant for the Sherwood Sandstone Group were MODFLOW and NAMMU two-dimensional models. These showed that the regional scale hydraulic conductivity values (relevant to a scale of a few thousand metres) found to be appropriate for the models were around an order of magnitude less than typical values from pumping tests in the area (relevant to a scale of a few hundred metres) and were more similar to those derived from core measurements (Heathcote *et al.* 1996). These results could imply the existence of widespread fracturing (enough to influence pumping tests) but with fractures not interconnected on a regional scale.

3.3.9 *Other evidence*

Sand pumping

Boreholes penetrating the poorly cemented Wilmslow Sandstone Formation are particularly vulnerable to pumping sand. Voids develop where cementation is negligible or absent and may not necessarily coincide with fractures (Campbell, J. personal communication). For example, two boreholes that penetrate the Wilmslow Sandstone at Manley Common [SJ 516 718] pump sand and are joined by a large void (Campbell and Nelson 1988). A borehole at Lower House, Mottram St Andrews [SJ 860 780], has had repeated problems with pumping sand (Peacock and Seymour 1980). The amount of sand pumped increases with the pumping rate, with little sand pumped at low rates. Pumping of some boreholes in the St Bees Sandstone Formation and the Kirklinton Sandstone Formation of the Carlisle Basin, may lead to sand influx and well development, suggesting that pumping can lead to development of fractures in these formations. Vines (1988) has described an example from the Scales Demesne borehole.

Fracture observations

The loss of a spring in the Winwick Area is recorded by de Rance (1890). A 30 m deep borehole [SJ 6152 9252] was drilled which hit a fissure that had hitherto fed the Spa Wells Spring. 200 m to the east. The spring then stopped flowing.

A fissure extends for 100 m across two boreholes at Padgate [SJ 629 900]. When one is pumped, the other's water level reacts very fast (Campbell, J. personal communication).

Modern enhancement of fractures and faults has resulted from coal mining. There are more faults than those shown on BGS maps. Subsidence steps occur around Winwick, just north of the M62, an area of intensive coal abstraction. Subsidence events in the area are exhibited by rampings or splits in the tarmac, and include events of 3 m in 500 m, 0.25 m in 35 m, 7cm over 60 cm and, at Hermitage Green 10 cm over 20 cm. There may also be fracture enhancement in the Vale of Eden due to gypsum mining (Thewsey, M. personal communication).

Fracture flow occurs from point sources at Agecroft Colliery [SD 800 013]. Water makes in coal mine workings pumped to the colliery until 1991, when shaft filling took place at the sites. There were 5 separate underground abstractions, with rates ranging from 20 to 250 gallons per minute. The inflows could be Carboniferous incrop leakages, which may in turn have been connected to the Permo-Triassic sandstones. As the water level recovers, acid mine water is likely to ascend via fractures (Thewsey, M. personal communication).

The Liverpool underground loop railway line was constructed when groundwater levels were lower. Now that they are rebounding, the tunnel has discrete areas of inflow. These are more common in the Wilmslow Sandstone Formation than the Chester Pebble Beds Formation, which is tighter and more fractured. The inflow areas also reflect how well the tunnel is sealed (Seymour, K. personal communication)

3.4 Southwest

The south-west region, illustrated in Figure 1.1, includes the Permo-Triassic sandstones of Somerset and East Devon. Table 3.1 summarises the evidence for fracture controlled hydraulic properties in the region.

The Permo-Triassic sediments of Somerset and East Devon lie unconformably on folded Carboniferous, Devonian and Palaeozoic basement. The main outcrop dips about 10 to 12° to the east, and Permian deposits in the north and west of the region occur as infills to large fault-controlled grabens. The grabens are bounded by east-west trending normal faults that were associated with substantial syn-depositional movement. There are some north-south structures associated with extension in the Triassic, and latter faulting in the region has a north-west-south-east orientation. A number of faulted blocks (Wellington, Halse and Bishop's Lyneard Blocks) are present north of Uffculm. These are bounded by east-west faults that displace the Triassic sandstones.

In general the Permian breccia aquifers of the region respond as fractured aquifers of relatively low storage and very variable permeability depending on the degree of fracture intersection and the local intergranular permeability of strata. The Permian breccias are made up of many different lithologies, and have only approximately 2% intergranular flow. Fractures provide most of the permeability, though the breccias tend to dewater on pumping, indicating the generally low permeability of these sediments, the local nature of the fracturing, and low storage coefficient. The sandstone aquifers (both the Sherwood Sandstone Group and the Permian sandstones) generally behave in an unconfined manner on a longer time scale, but in a confined way over the period of a short pumping test. They exhibit both barometric and tidal efficiency; but have a relatively long time response to pumping, with equilibration taking years rather than days. Allen *et al.* (1997) compared the bulk well hydraulic conductivity and core hydraulic conductivity data for the region. The laboratory values were significantly lower than the average hydraulic conductivity determined from pumping test transmissivities, and generally the highest intergranular hydraulic conductivities corresponded with the lowest pumping test conductivities.

3.4.1 *Geological Surveys*

There have been no major studies into faulting in the region. There are a number of faults indicated on geological and hydrogeological maps, however, evidence for faults is usually inferred from other data. For example, the existence of extensive small scale faulting has been inferred from road cuttings which show different sediment types on either side of the road in the area of Feniton [SY 108 995] (Johnston, P. personal communication). Faults are also inferred where nearby boreholes appear to encounter greatly differing transmissivities. At Kersbrooke [SY 062 832] a pilot borehole was drilled and tested; it was productive and a good public supply yield was predicted from the site. The production borehole was subsequently drilled on the same site a few metres away, but it had a very low yield. The change in yield between the boreholes was attributed to the existence of a fault, rather than to lithological changes between the two boreholes. Faulting within the Crediton Breccia Formation of the Permian sandstones and breccias of the south-west often gives rise to spring lines. These may be the result of faulting juxtaposing permeable and less permeable horizons.

3.4.2 *Borehole geophysics*

Throughout the south-west region there is little logging data available, flow logging data in particular is generally absent. The exception to this is the extensive conductivity logging carried out as part of the

Otterton saline groundwater study (South West Water Services Ltd, personal communication). This suggests possible near surface saline ingress along an ill-defined front. The location of saline water could be either fracture or lithologically dependent. Continuous conductivity logs have shown great temporal variations in conductivity, indicating active fracture flow, with changes in the salinity of the groundwater moving through the fracture system.

Very poor correlation was seen between lithological logs of the geographically close Harpford and Dotton boreholes (Tubb, C. personal communication). Harpford 5 [SY 094 908], Harpford 6 and 7 [SY 092 908] and Dotton borehole 5 [SY 087 892] encountered different lithologies, and also had markedly different responses to pumping. The existence of a fault between the two sites was inferred although there is no surface evidence for its existence. Geophysical logging evidence from two other boreholes has indicated mainly fracture flows (in one borehole, predominantly from over 100 m bgl).

3.4.3 *Hydraulic tests*

Numerous step tests and short constant rate pumping tests have been performed across the region. The tests have been analyzed but the results have not been investigated regarding the effects of fractures. It is difficult to separate the effects on drawdown of changes in lithology, from those associated with boundaries, particularly as observation borehole data rarely exist. Delayed yield effects are commonly seen in pumping tests, and these tend to mask other phenomena: so that fracture effects are not generally seen. Even large boundaries, such as rivers, are not always seen in pumping test data. For instance, a pumping test at Greatwell borehole, within a few hundred metres of the river Otter, did not indicate a recharge boundary. This may be because the pumping tests are generally short: step tests only last up to 3 days, and constant rate tests are generally up to a day long.

Exploratory borehole No 2 [SX 9128 9880] in the west of the region penetrates only the Dawlish Sandstone Formation, passing through layered sandstones, mudstones and occasional breccias. Extensive pumping tests were carried out with many observation boreholes. These indicated a mean transmissivity of 74 m^2/d for the pumped well data, with 62 m^2/d for the deep observation well, and 42-140 m^2/d for various shallow observation boreholes. By allocating appropriate values of hydraulic conductivity to the various lithologies in the borehole the intergranular transmissivity was estimated to be 26 m^2/d, indicating that most of the transmissivity is from fractures (Davy 1981).

The Permian breccias have very variable transmissivities, generally less than 300 m^2/d and often of the order of 50 m^2/d, depending on borehole fracture intersection. At Colebrooke [SS 7570 0160], the mean intergranular hydraulic conductivity was 8×10^{-4} m/d compared to a field hydraulic conductivity of around 0.3 m/d, again indicating predominantly fracture flow. Fractures were also indicated at Burrow Farm production borehole [SX 941 995], where a step-test was carried out, during which water levels fell unexpectedly within constant rate steps. Water levels began to stabilise over a few hundred minutes before dropping again suddenly, probably due to the dewatering of discrete sets of fractures. The ratio of intergranular to fracture flow is very variable.

A pumping test at Kersbrook [SY 062 832], with measurements from three observation boreholes, resulted in a range of transmissivity values where apparent transmissivity increased with distance (up to about 50 m) from the production borehole. This apparent transmissivity variation was inferred to be due to a 'skin effect' around the borehole, where the aquifer was damaged during drilling, rather than the result of changes within the aquifer itself (written communication L. Clarke).

3.4.4 *Hydrograph data*

There are hydrograph data held for about twenty sites in the region, but some observation boreholes record perched water levels, which may be misleading. The hydrographs generally show relatively smooth annual curves with no evidence of highly rapid fracture recharge in response to individual rainfall events (Johnston, P. personal communication), although hydrographs from observation boreholes within the

Budleigh Salterton Pebble Beds show a more peaky response than those in the sandstones. This could be because the Pebble Beds are more permeable due to the presence of fractures and/or due to poorly cemented horizons, allowing more rapid recharge to occur especially where the water table is near the surface (South West Water Services Services Ltd, personal communication).

3.4.5 *Sand pumping*

Sand pumping has locally been a problem in the Otter Valley area. Two boreholes had particular problems with sand, especially during summer months when groundwater levels are low and the lower part of the boreholes filled with sediment. It is uncertain whether the ingress of sediment was due to formation collapse around the borehole, or washing out and development of fractures (MRM Partnership, 1989).

3.4.6 *Geochemical techniques*

Geochemical studies in the region include a study by Walton (1978, 1982) and an investigation of saline intrusion carried out for South West Water (South West Water Services Ltd, personal communication). Water quality is regularly monitored, especially for public water supplies, but individual analyses have not been collated and interpreted on a regional basis, except for nitrate values (Johnston, P. personal communication). There is no geochemical evidence for significant structural control on water chemistry in the region.

3.4.7 *Modelling studies*

The Triassic aquifer in the Otter Valley has been modelled by MRM Partnership (1989). The river baseflow has been modelled satisfactorily, but the model is not so good at matching groundwater heads measured in boreholes, though the pattern of groundwater level fluctuation is reproduced. Additionally, the water balance in the model is somewhat uncertain. The study indicated that there is flow between the Otter Sandstone and the Budleigh Salterton Pebble Beds, and a 2-D regional finite difference model used a hydraulic conductivity of 1.75 m/d. This is within the upper range of the core permeabilities and at the lower end of the average borehole hydraulic conductivities and suggests that on a regional scale fractures may not be significant in groundwater flow. This is supported by the observation that the model has a long response time (of the order of years). However, a review of the model undertaken for South West Water (South West Water Services Ltd, personal communication) suggests the need to conceptualise fracture distribution and its effects on transmissivity.

Flow path protection zone modelling currently being carried out does not take account of fracture distribution.

3.4.8 *Other studies*

In the Otter Valley the River Otter is in partial hydraulic continuity with the aquifer. There appears to be local flow from the river to a number of boreholes located close to the river, but characterisation of the river-aquifer interaction is difficult. Boreholes near the River Otter have higher specific capacity values, because of induced river recharge on pumping and attempts to determine the river contribution to pumped waters indicated about one third to one half river water contribution, possibly greater at some sites. Water temperatures in some boreholes near to the river show similar changes to that in the river, and one tracer test near the River Otter indicated connection of the river with the borehole. However, the role of fractures in the river-aquifer interaction is uncertain.

Generally fractures and faults are not taken into account when siting boreholes. Within the Otter Valley area, the main constraints are the shape of the valley and extent of the aquifer outcrop, and borehole sites are chosen to minimise derogation of surface watercourses, especially the river Otter.

4. CONCEPTUAL MODELS OF FRACTURE FLOW IN THE PERMO-TRIASSIC SANDSTONES

This section presents a series of conceptual models of the possible relationships between fracture distributions and flow in the Permo-Triassic sandstones. The purpose of the conceptual models is to bring theoretical and empirical observations together into consistent descriptions of how fractures and sedimentary architecture may affect flow in the sandstones. Consequently, the models are based on the expected distributions of bedding plane fractures, joints and faults and sedimentary architecture described in the Appendix, and on field observations of fracture related flow phenomena described in Section 3. Using the conceptual models, it should be possible to make a series of predictions about the hydraulic behaviour and characteristics of the fractured Permo-Triassic sandstone aquifer. These predictions could be tested using a variety of techniques, and the conceptual models could be used as the basis for the design of field, laboratory or modelling studies.

The conceptual models are not definitive, rather they are designed to illustrate a range of possible relationships between fracture distributions and flow. The first model is designed to show possible flow behaviour in a sandstone aquifer where bedding plane fractures tend to dominate flow to a borehole, and where lithological control of the bedding plane fracture distribution is significant. The second model is designed to illustrate some of the possible interactions between bedding plane fractures and faults, and how this may effect flow to a borehole. The third model is intended to illustrate the possible hydraulic effects of situating a borehole near a hydraulically significant fault zone.

4.1 Bedding Plane Fracture Model

Lithological variation is likely to be an important factor in the distribution and size of bedding plane fractures where faults have limited hydraulic influence or where bedding plane fractures dominate the hydraulically significant fractures. Qualitative field observations appear to suggest that the most pronounced bedding plane fractures (largest lateral extent and widest apertures) develop at abrupt changes in lithology, *i.e.* at shale-, mudstone-, siltstone- or marl-sandstone contacts, or where one of the lithologies is either finely laminated or contains strong bedding plane parallel fabrics. These sort of lithological changes may be found in a range of fining upward cycles associated with channel deposits, but are generally best developed when relatively fine-grained overbank deposits overlie coarser channel sediments. The lateral extent of the overbank deposits may be significantly greater than the channel deposits, and consequently the associated bedding plane fractures may also be laterally extensive compared with bedding plane fractures within the channel sandstones. An example of the lateral extent of hydraulically significant bedding plane fractures was given by Michalski and Brittan (1997), who described hydraulically conductive bedding plane fractures with lengths in excess of 500 m in a series of mudstones and shales from the Newark Basin, New Jersey.

Figure 4.1 is a highly schematic illustration of the possible lithological controls on the lateral extent of bedding plane fractures. A borehole intersecting a series of sandstones and shales will intersect a range of bedding plane fractures that can be divided into two broad populations. The bedding plane fractures within the channel deposits may be expected to follow one distribution with a relatively small mean size (where the maximum size should not be greater than the maximum preserved channel width). A second bedding plane fracture size population with a larger mean size should be associated with the fractures located at the base and/or top of overbank sediments. Clearly, more than two types of bedding plane fracture population may be present. For example, where there are a variety of channel fill architectures they may impart characteristic bedding plane fracture characteristics, and aeolian deposits may be interspersed in the sequence. In addition, the functional form of the fracture size populations is entirely unconstrained (e.g. normal-, log-normal or another distribution). However, the smaller bedding plane fractures within the channel deposits should be significantly more frequent than the fractures associated with overbank deposits.

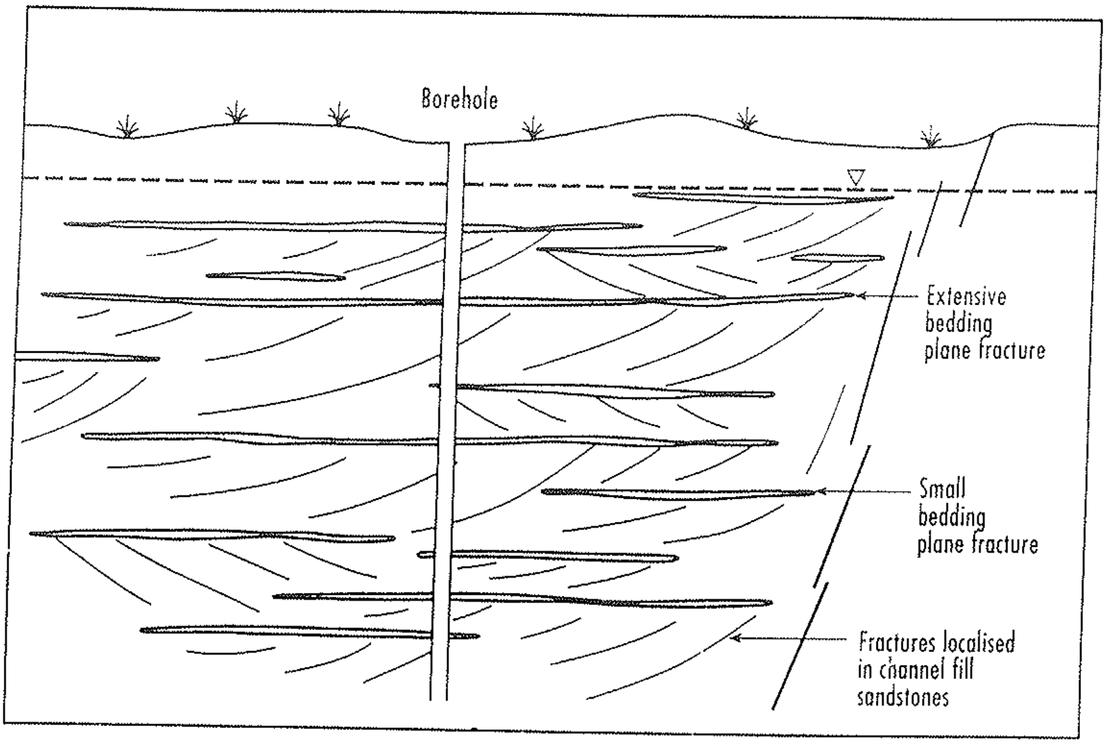

Figure 4.1 **Schematic bedding plane fracture model**

What are the possible hydrogeological significances of this conceptual model? The model suggests that most of the bedding plane fractures intercepted by the borehole may only have a limited lateral extent (maximum size not greater than maximum preserved channel width), and therefore, unless they are connected to other hydraulically significant elements of the fracture system (pervasive and conductive joint network, or conductive faults) they will only provide limited hydraulic continuity. The effect of such fractures of limited extent on the borehole's productivity is likely to depend on the hydraulic conductivity of the matrix; if the matrix has low permeability then the fractures will produce little flow, however in a permeable matrix they may be very productive. As Price (1994) has pointed out, the presence of large productive fractures in boreholes in permeable sandstones does not necessarily imply fracture flow in the formation.

The relatively small number of the bedding plane fractures associated with shale-sandstone contacts may provide significant lateral hydraulic continuity and may therefore be important for pollutant transport processes. The contribution of such fractures to borehole productivity may be less affected by the properties of the matrix and more by the geometrical properties (e.g. fracture aperture and channelling) of the fractures themselves.

In addition to the above, the density, lateral extent, and aperture of bedding plane fractures may all be expected to reduce systematically with depth due to enhanced stress relief and fracture development near the ground surface (Merin, 1992). Therefore the hydraulic significance of bedding plane fractures may be expected to decrease with depth.

It should be noted that the relationship between bedding plane fractures and sedimentary architecture described above is highly simplistic. Fracturing intensity and characteristics (including bedding plane fractures) will not only depend on the overall sedimentary architecture (*e.g.* fining upward cycles, overbank deposits, ratio of channel to aeolian deposits), but will also be highly sensitive to the style of cementation and the detailed diagenetic, and tectonic history of the sediments. These factors have not been considered in the model described above.

4.2 Bedding Plane Fracture - Fault Interaction Model

A general structural framework for fracture systems in sandstones (independent of any lithological effects as discussed above) can be developed (Figure 4.2) based on the expected distributions of bedding plane fractures, joints and faults as described in the appendix and in Table A1.2. This structural framework can be used as a basis for discussion of the relationships between bedding plane fractures and faults.

For a given region, the sandstones are envisaged as consisting of fault-bounded segments, or blocks, with a scale invariant fault size distribution at the borehole to catchment scale. If bedding dip is small, within each fault-bounded segment the dominant sub-horizontal structures are bedding plane fractures that are assumed, for simplicity, to be continuous in this model. The spacing of the bedding plane fractures is scale dependent, being a function of sedimentary architecture and local bedding thickness distributions, but their size (lateral extent) may be controlled by the scale independent spacing of bounding faults. Subordinate to the bedding plane fractures is a network of smaller, scale dependent, joints and false-bedding plane fractures (not shown in Figure 4.2). These smaller fractures are expected to be relatively predictable in their occurrence, scaling as a function of bedding or false-bedding plane thickness. Because of their small apertures they are probably hydrogeologically much less significant than faults and bedding plane fractures (Bloomfield 1996). They are not considered further in this section.

In reality, different components of the fracture system may be developed to differing intensities in various tectonic settings and in response to lithological variation, and fractures may change significantly in character with depth. Therefore, it would be desirable to develop a conceptual structural framework on a local or sub-regional basis, and not across an entire basin. For example, the spacing of bedding plane fractures will depend on the lithology: in the Helsby Sandstone of the Cheshire Basin bedding thickness may typically be in the range 10 cm to 10 m, and the best developed and most laterally continuous bedding plane fractures (which are associated with thin marls at the top of fining-upward cycles) may have a spacing of about 10 to 20 m. These latter values may be more appropriate for use in the structural framework. In comparison, bedding plane partings are largely absent in the poorly consolidated Wilmslow Sandstone, and there may only be one or two laterally continuous partings in a 50 or 100 m section.

Given that the sandstone matrix is permeable, how would water be expected to flow through the structural model in Figure 4.2? If the borehole was pumped, where would the water be drawn from in the surrounding rockmass, and what part of the fracture network, if any, would contribute to flow? Flow in the system depends on a balance between the permeabilities of the different components of the structural framework. For example, if we assume that the matrix is significantly less permeable than the bedding plane fractures then the bedding plane fractures should contribute to flow much more easily than the matrix, and so the bedding plane fractures should contribute most of the observed hydraulic conductivity at the well when it is pumped. But what happens when a bedding plane fracture intercepts a fault? If the fault throws material of essentially similar permeability as the unfractured matrix against the fracture then the effect will be simply to terminate the fracture. If the fault throws essentially impermeable material (e.g. fault gouge) against the fracture then the effect will be to provide a hydraulic barrier. If on the other the fault terminates in the damage zone around the fault there is the possibility of this acting as a recharge boundary for the fracture. In addition, the significance of these modes of fracture/fault intersection will depend on the relative permeability of the fracture and matrix and the distance from the pumped well; thus the hydraulic properties of a bedding plane fracture in a permeable matrix may be relatively unaffected by a fault at a significant distance from the pumping well, whereas such a fracture in a poorly permeable matrix may be significantly affected by a nearby fault.

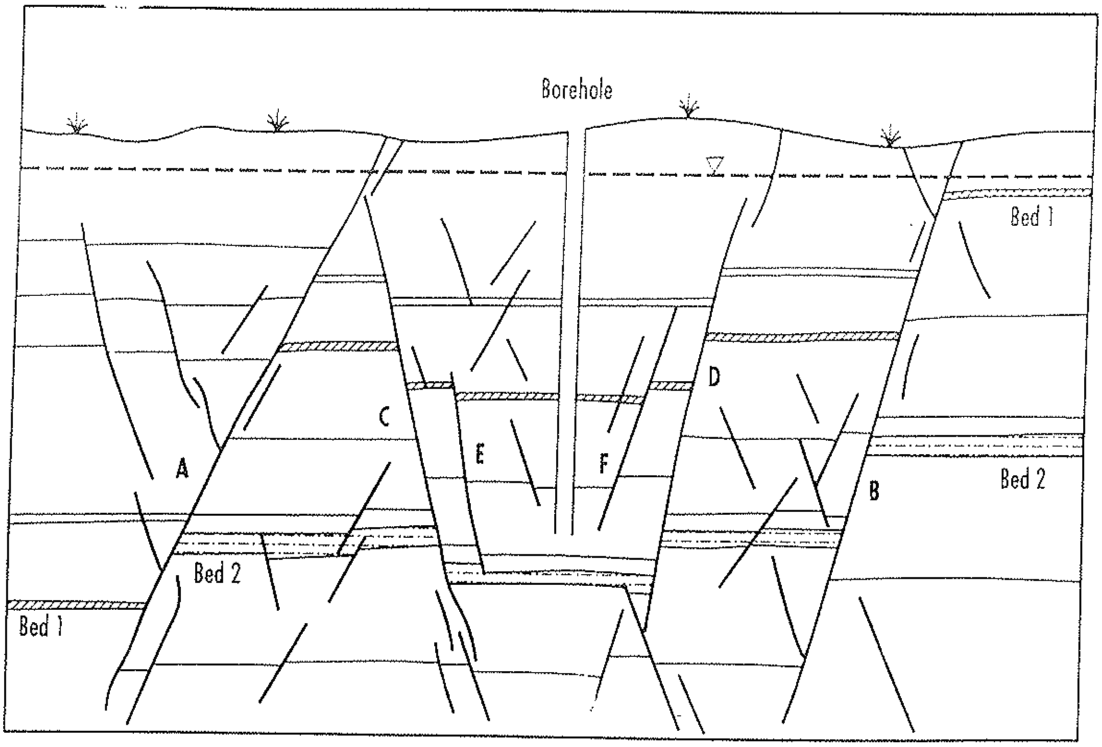

Figure 4.2 General Structural framework for fracture systems in sandstones

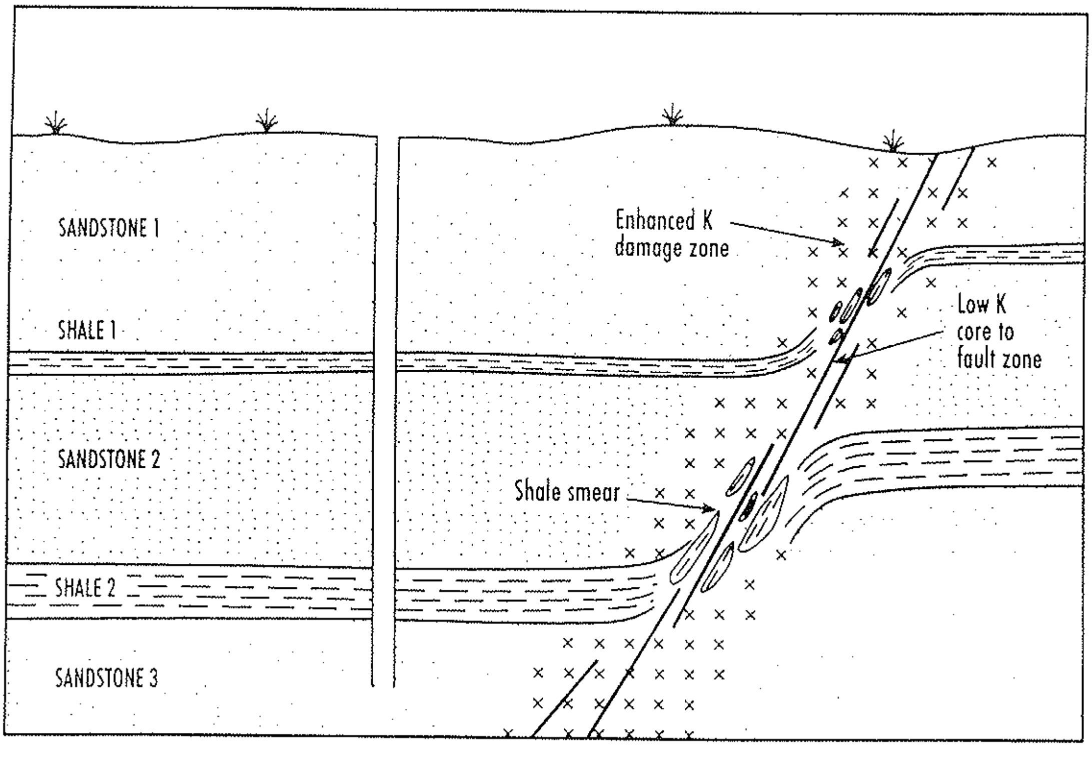

Figure 4.3 Schematic fault model

4.3 Fault Model

Figure 4.3 shows a fault displacing a series of sandstone and shale beds of varying competence and matrix hydraulic characteristics. If a borehole is located near the fault what effects might the fault have on head distributions or flow to the well if the well is pumped? Enhanced hydraulic conductivity may be expected if the borehole accesses both bedding plane fractures in the sandstone units and the zone of dilational damage around the fault. Relatively rapid movement of groundwater may be expected parallel to the fault plane. Depending on the local head gradients, rapid transport from depth, along the plane of the fault, or from ground surface may both be possible. However, the presence of shales intersected by the fault may limit flow in a vertical direction parallel to the fault plane. The zone of dilational damage may preferentially develop only in the more porous sandstones. This would have the effect of restricting enhanced flow near the fault plane to sub-horizontal volumes in the units most susceptible to dilational damage.

The extent to which the fault may act as a hydraulic barrier depends on a range of factors including: fault size and displacement, the local sedimentary sequence, particularly the proportion of clay-rich lithologies, and the structure of the core of the fault zone. Fine grained cataclastic slip zones in the core of the fault zone, cementation of the fault zone and shale smears incorporated into the fault zone may all act to reduce the permeability of the core of the fault and would significantly reduce flow or the propagation of heads across the fault. However, it should be noted that displacements on faults and the 'style' of deformation features at their core may vary greatly along their length. For example, in an interbedded sandstone-shale sequence faults may be restricted to certain sandstone units while other sandstones and the shales may only exhibit a flexure. Consequently, it may sometimes be more appropriate to visualise some faults with small or moderate displacements as potentially leaky baffles rather than sealing structures.

5. SUMMARY AND FURTHER WORK

5.1 Summary

The following conclusions can be drawn from the work summarised in this report:

i) Fractures are known to have important effects on the hydraulic structure of the Permo-Triassic sandstones. The evidence for this comes from a range of techniques including geological observation and the interpretation of geophysical, geochemical, mineralogical and hydraulic data.

ii) The two types of fracture that are most hydrogeologically significant are bedding plane features and faults.

iii) Bedding plane fractures are common in the aquifer in all areas of the country. They may develop along any mechanically weak bedding plane surface, but they appear to be preferentially developed at relatively shallow depths and at discrete lithological contacts such as shale-sandstone boundaries. This type of boundary is often associated with overbank deposits and may have a lateral extent of a few hundred metres. Bedding plane fractures in channel-fill sandstones generally only have a lateral extent of a few tens of metres.

iv) Bedding plane fractures appear to be most hydrogeologically significant at depths less than 200 mbGL. While these fractures can radically affect the response of boreholes to pumping it is unclear how interconnected they are on a regional scale; however the present evidence suggests that while they may be ubiquitous they do not extend as hydraulically connected features for more than a few hundred metres.

v) Faults are common structures within the Permo-Triassic sandstones. They vary in size from less than a metre to tens of kilometres, but within a region they may exhibit scale-invariant (fractal) size, spacing and displacement characteristics. Consequently, it may be possible to predict some regional fault characteristics from local outcrops. Faults are complex structures whose geometry and style are as much a function of the matrix properties of the rocks they displace as they are of the deformation history of the fault. Faults are rarely planar features, they generally consist of multiple subparallel slip surfaces. Significant grain size reduction associated with cataclastic deformation causes the development of fault gouge in the core of fault zones. Fault planes may be the site of cementation and shale smears may be incorporated into fault planes where faults displace shales and mudrocks. Marginal to the fault zone porosity may be increased by pervasive microfracturing of the matrix. Coarser, more porous, less well cemented sandstones may be particularly susceptible to the development of enhanced porosity.

vi) Hydraulically, faults have been interpreted as having a range of effects, from acting as recharge boundaries to causing the hydraulic isolation of blocks of aquifer. A recurring model (Fowles and Burley 1994, Gibson 1994, Knott 1994) is that of a central fault core comprising low permeability fault gouge, surrounded by a high permeability damage zone. Thus, potentially, faults can act as linear zones of high permeability and barriers to cross-flow at the same time.

vii) Sand pumping is a significant problem in some production boreholes and individual case studies can relate pumped volumes to specific pumping regimes. However, there may be a variety of causes of sand pumping, e.g. development of poorly cemented horizons, of induced fractures, of bedding plane fractures and/or of faults. It is not yet possible to predict the occurrence of sand pumping as the phenomena has not yet been systematically investigated.

viii) Good data describing the hydrogeological effects of fractures in the Permo-Triassic sandstones are very limited. Much of the evidence is anecdotal in nature and there are very few interdisciplinary studies.

5.2 Requirements for Further Work

5.2.1 *General*

From the problems outlined in Section 1, the discussion in Section 4 and the above summary it is suggested that research concentrates on two main areas; (i) the investigation of the likely extent of bedding plane fractures, particularly as potential routes for rapid transport of pollutants and, (ii) the investigation of the hydraulic characteristics of faults, in particular whether they are likely to act as barriers to pollutant migration, hydraulic barriers for resources or alternatively rapid transport routes or recharge boundaries. Other useful areas of research would be the interaction between bedding plane fractures and faults, and the hydraulic properties of joints, however these are at present regarded as having a lower priority.

Investigation types

For the two main areas of research, it is considered that there are broadly three types of investigation that should be considered:

a) site specific, multidisciplinary
b) new tests at existing sites or on existing material
c) analysis of existing data

with costs generally decreasing in the order a>b>c. In addition, numerical modelling is likely to be useful for all three types of research.

5.2.2 *Bedding plane fractures*

The main issues with bedding plane fractures are to improve understanding of the nature and controls on both the fractures generally and hydraulically significant bedding plane fractures in particular and to investigate the relationship between the two. In particular the questions below are pertinent.

- What is the typical lateral extent of bedding plane fractures, and what are the physical controls on lateral extent? Is it lateral lithological variations or principally fault spacing distributions?

- What constitutes hydraulically significant bedding plane fractures? Should they be defined in relation to average matrix conductivity, or in absolute terms?

- What proportion of bedding plane fractures are hydrogeologically significant?

- What fraction of a hydrogeologically significant bedding plane carries most of the groundwater flow (i.e. to what extent is channelling significant)?

- What are the typical characteristics (e.g. lateral extent, spacing, aperture) of the hydraulically significant bedding plane fractures?

- Can bedding plane fractures and hydraulically significant bedding plane fractures be correlated with parameters such as depth, or with lithology in a given region, catchment, or site, and if so how and why do these correlations vary? Can we make any informed predictions concerning the distribution of hydraulically significant bedding plane fractures given the geology and location?

Of the above issues, perhaps the most important from both the resource and pollutant transport standpoint are the improvement of understanding of the lateral extent of the hydraulically significant bedding plane fractures, and to find ways of predicting these from other, more accessible, data such as lithology, geophysical logs or hydraulic tests.

5.2.3 *Faults*

The investigation of the hydraulic effects of faults in the sandstones is probably best based on testing the hypothesis outlined in Section 4, i.e. that faults may act as planes of low permeability bordered by damage zones of high permeability. This leads to specific questions to be answered such as those below.

- Can the model be shown to be correct in general terms i.e. is the relationship K(fault damage zone)>K (undisturbed aquifer)>K(fault core) valid?
- What are the controls on the three types of permeability? For example how are they affected (relatively) by the proportion and distribution of argillaceous material? or by fault type, or throw?
- Can critical fault displacements be recognised on a local or regional basis, where faults with displacements equal or greater to the critical displacement act as barriers?
- What controls the widths of the fault cores and damage zones? Also are fault damage zone widths symmetrical around fault cores?
- How does permeability associated with faulting vary with depth, or with vertical variations in lithology?

5.2.4 *Combination studies of bedding plane fracture - fault interaction*

The interaction between bedding plane fractures and faults will have an important role to play in the mechanisms of fracture flow in the Permo-Triassic sandstones. Indeed it is unlikely that any study of fault hydrogeology will exclude the effects of some bedding plane fractures and faulting may well be an important factor in many studies of bedding plane fractures. The separation of the investigations suggested above is for the sake of simplicity in order that the two types of mechanisms may be studied where they are individually most dominant. At this early stage, to investigate specifically systems where the combination of factors is anticipated would perhaps require unreasonably large resources for research.

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APPENDIX

A1. DEFINITIONS AND THEORETICAL BACKGROUND

This section introduces a number of definitions and basic principles concerning the geometry and hydraulic characteristics of fractures in clastic sedimentary rocks that are used in the development of a conceptual model of fracture flow in the aquifer, Section 4.

A1.1 Definitions of Fractures

Fractures are discontinuities in the rockmass that accommodate strain by brittle failure. They define discrete, planar breaks within the matrix of the rock and are present in the Permo-Triassic sandstone aquifer over a large range of size scales. A group of parallel or sub-parallel fractures are a *fracture set* and all fractures in the rockmass can be referred to as a *fracture network* or *fracture system*. The *matrix* consists of unfractured rock where any planar fabric elements are due to sedimentary or diagenetic processes and are not due to fracturing.

Fractures have two approximately parallel surfaces bounded by a fracture front, or tip line. Three basic modes of displacement can be recognised at the tips of fractures (Paterson 1978). These are illustrated in Figure A1.1a to A1.1c. Mode I fractures are opening mode fractures where the displacement is perpendicular to the plane of the fracture. Mode II fractures are shear fractures where the displacement is parallel to the crack plane and perpendicular to the tip line and Mode III fractures are shear fractures where the displacement is parallel to the fracture plane and the tip line. Fractures may be open, or partially or wholly filled. Fracture fills may consist of loose or consolidated sands and/or clays, either derived from the adjacent matrix, precipitated in-situ, or brought in from elsewhere. The fractures may also be cemented. Fracture fills may be relatively recent, or they may have developed as a consequence of deformation processes at the time of fracture formation. The nature of fracture fills in the Permo-Triassic sandstone aquifer and their possible influence on the fracture hydraulics will be discussed latter, however, it should be noted that regardless of whether a planar discontinuity is open or filled it is still referred to as a fracture in this report. Veins are therefore included.

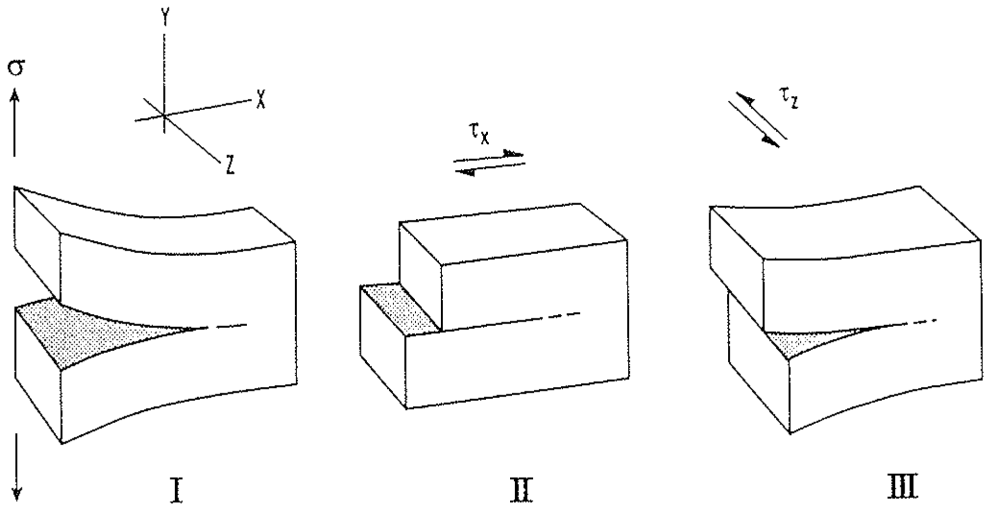


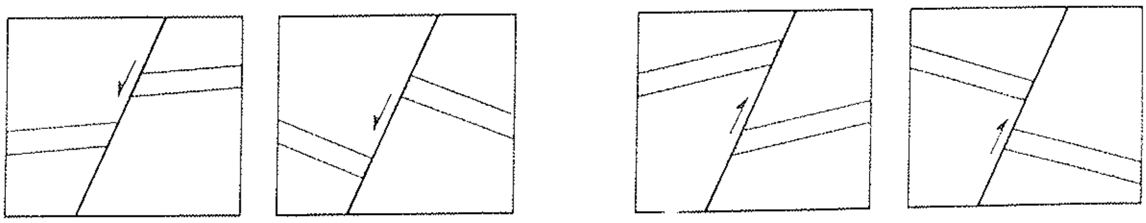
Figure A1.1 **Three basic modes of displacement at the tips of fractures. Mode I, displacement normal to the fracture plane, Mode II, displacement parallel to the fracture plane and normal to the fracture edge and Mode III, displacement parallel to the fracture plane and edge (after Paterson 1978)**

It is helpful to distinguish four specific types of fracture in clastic sedimentary rocks, *i.e.* bedding and false-bedding plane fractures, joints and faults. This is because different types of fracture form under different geological conditions and in response to different stress histories or to specific stress states, and as a consequence, they accommodate strain in different manners. This may lead to systematic, and potentially predictable, differences in the geometrical distributions of each type of fracture (Gillespie *et al.* 1993, Bloomfield 1996).

Bedding plane fractures and *false-bedding plane fractures* are structures that are located at discrete lithological boundaries. Lithological variations across these boundaries may be relatively pronounced, as for example, at the contact between marls and sandstones, or they may be subtle, consisting only of changes in the degree or nature of cementation of the matrix. Bedding plane fractures may be laterally persistent when they are developed in association with areally extensive transitions in lithology, whereas false-bedding (or cross-bedding) plane fractures are restricted in scale to the size of the controlling cross-bedding plane features. Generally, bedding plane and false-bedding plane fractures are opening mode, or Mode I, fractures (Figure A1.1a).

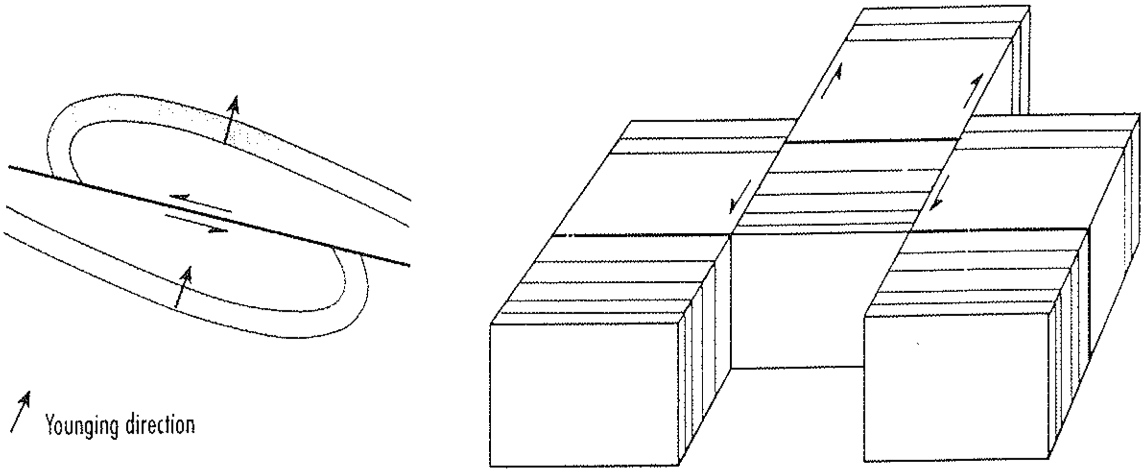
Joints are also opening mode, or Mode I, fractures (Pollard and Aydin 1988). In contrast to bedding plane and false-bedding plane fractures, they characteristically form at high angles to bedding and/or false bedding surfaces and are usually bounded by bedding plane fractures or bedding plane surfaces. A group of parallel or sub-parallel joints is referred to as a *joint set* and all the joints within a given rockmass may be collectively referred to as a *joint network*. In flat lying sedimentary sequences the most commonly observed joint pattern in surface exposures is that of two or three mutually perpendicular joint sets, *orthogonal joints*, with two sets perpendicular to bedding and one set parallel to bedding. Where two joint sets intersect at an oblique angle and are related (or as a consequence of formation in the same stress field) they are referred to as *conjugate joints*.

Faults are fractures that exhibit a shear displacement parallel to the fracture surface, *i.e.* are Mode II or Mode III fractures (Hancock 1985), and can be described according to the sense of displacement. If the displacement across the fault causes local horizontal extension the fault is a *normal* or *extensional fault*. If the displacement causes local horizontal contraction or shortening the fault is either a *reverse fault* (for fault dips that make a large angle with the horizontal) or a *thrust fault* (for faults that make a shallow angle with the horizontal). A *wrench fault* is a fault where the displacement is predominantly parallel to the horizontal. *Oblique slip faults* are a combination of wrench faults andeither extensional or reverse faults. Each of these types of fault are illustrated schematically in Figure A1.2. In 3-D, single fault surfaces can be modelled as planar ellipsoidal discontinuities, where the maximum displacement is near the centre of the fault and minimum displacement is along the edge, or tip line, of the ellipsoid. In reality interaction of neighbouring faults affects both the idealised shape and displacement distributions in the plane of the faults. Normal, or extensional faults often occur in conjugate sets and may define a *fault-bounded block* or fault blocks. In an area of conjugate faulting if there is a dominant fault set these faults are referred to as *synthetic faults* and smaller conjugate faults are referred to as *antithetic faults* (Figure A1.2). Faults are rarely found in isolation and small faults are commonly clustered near larger faults. These concentrations of faults are called *fault zones*.



a) Normal faults

b) Reverse faults



c) Thrust fault

d) Wrench faults

Figure A1.2 **Schematic illustration of each of the major classes of fault, normal, or extensional faults, reverse faults (including thrust faults) and wrench faults (after Whitten and Brooks 1972)**

In coarse sandstones a characteristic set of structures may develop in faults zones as illustrated in Figure A1.3b (after Fowles and Burley 1994). The fault zone will contain one or more striated *slip surfaces* (discrete faults with measurable displacements), *cataclastic slip bands* and *granulation seams*, zones that do not show discrete displacement but consist of planar deformation features sub-parallel to the trend of the fault zone where the matrix of the sandstone has undergone brittle deformation, and *cataclastic slip zones*, zones of anastomosing slip bands with undeformed sandstone between. The slip surfaces may show an aligned mineralisation indicating the slip direction of the last or several most recent slip events, but they do not give an indication of the complete displacemtn history. Where the rockmass consists of a variety of lithologies, *i.e.* coarse and fine sandstones and shales, or when a fault zone has had a complex history of movements, crushed, damaged or deformed matrix materials may be found within the bounding surfaces of a single fault or in a fault zone. These are referred to as *fault gouge* or *fault breccia*. Fault gouge is relatively fine-grained and fault breccia relatively coarse. If very soft or ductile rocks are involved in faulting, such as shales and mudrocks, these may become incorporated onto the slip surface to form *shale smears*, Figure A1.3a (after Gibson 1994).

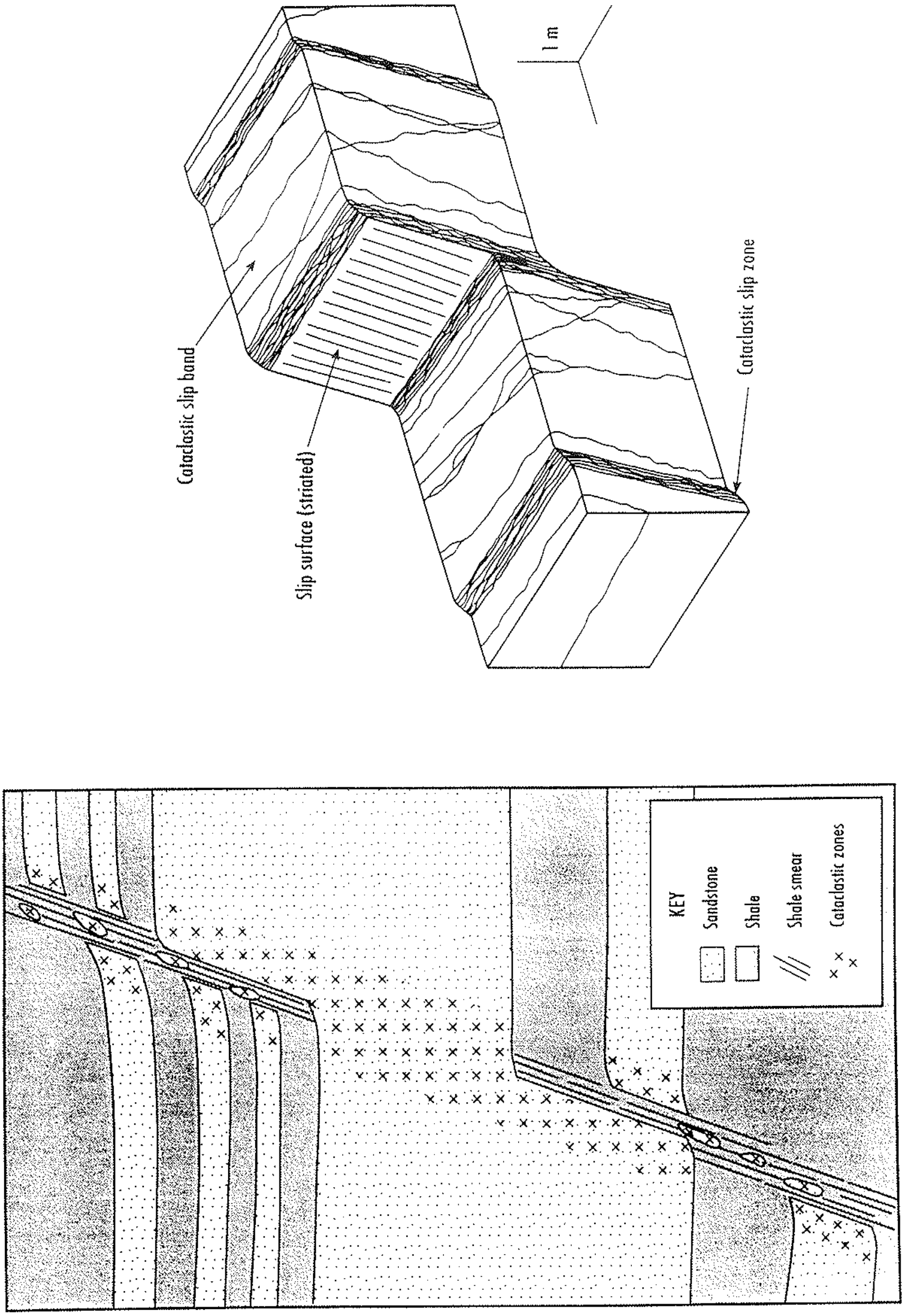


Figure A1.3 Schematic illustration of a characteristic set of structures may develop in fault zones in coarse sandstones (after Gibson 1994, Fowles and Burley 1994)

A1.2 Fracture Characteristics

A number of characteristics can be ascribed to individual fractures and to fracture sets. As most fractures can only be viewed in 2-D sections, for example at quarry or cliff face exposures, or on geophysical sections such as borehole televiewer logs, the observed *fracture size* is defined by the length of the chord formed by the intersection of the fracture plane and the section plane. This will lie between the true maximum and true minimum fracture lengths. Consequently, all fracture lengths should be treated as *fracture trace lengths* and not as true lengths. *Fracture orientation* can be described by two measurements, the direction of trend, or *strike*, of the fracture plane and the degree of *dip* of the fracture plane measured perpendicular to the strike of the fracture. The *aperture* of a single fracture is the perpendicular distance between the two bounding surfaces, although it should be noted that in natural fractures the aperture is unlikely to remain constant along the trace length and the aperture of a fracture could be characterised by an aperture distribution with some mean value. The *spacing* of fractures in a single fracture set (sub-parallel fractures) is measured as the perpendicular distance between two fractures. In natural fracture sets the spacing between successive pairs of fractures is unlikely to be constant and the mean spacing may be a more appropriate description of the spacing characteristics. The 'spacing' of all fractures in a fracture network can be measured by counting the frequency of intersections along a line sample, however, in this case it is more appropriate to consider this a measure of the *fracture density* of the entire fracture network.

Potentially, the connectivity of fractures in the Permo-Triassic sandstone aquifer is of importance to the hydraulic behaviour of the fracture network, but unfortunately connectivity is very difficult to define. Fracture *connectivity* may be loosely defined as the degree to which individual fractures are linked and this is likely to be a function of parameters such as fracture size, orientation and spacing. There is no complete theoretical description of a fracture connectivity function, however Rouleau and Gale (1985) proposed a simple connectivity index for two fracture sets (in 2-D) that shows the dependence of fracture connectivity on fracture length and fracture spacing (Figure A1.4). They defined a *fracture connectivity index* for two fracture sets as follows;

$$I_{ij} = l_i/s_j \sin \gamma_{ij}$$

where I_{ij} is the connectivity index between the i and j fracture sets, l_i is the mean trace length for set i, s_j is the mean spacing of set j, and γ_{ij} is the average angle between the fractures of set i and set j. Usually, I_{ij} may be expected to be different from I_{ji}. For an idealised system of two fracture sets the connectivity index of one set becomes large as the trace length of that set increases, and/or when the spacing of the second set is small, and/or when the angle between the two sets increases. The index becomes vanishingly small if the two sets approach parallelism.

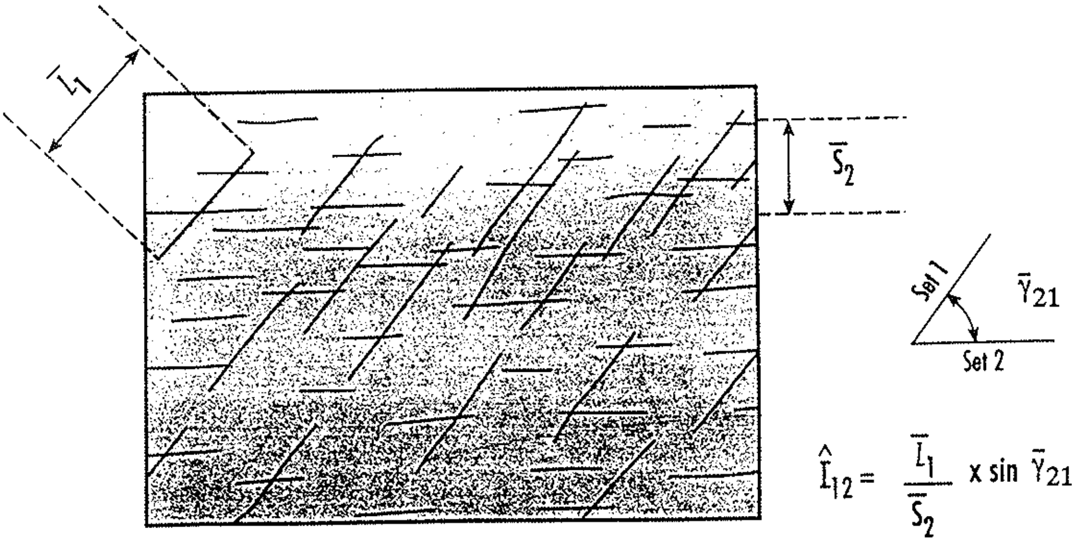


Figure A1.4 **Schematic illustration of the connectivity index between two fracture sets (after Rouleau and Gale 1985)**

However, a note of caution must be sounded when assessing the importance of fracture connectivity in groundwater flow and transport. Odling and Roden (1997) modelled the transport of contaminants in fractured rocks with significant matrix permeability using a variety of natural fracture geometries. They noted that although fracture connectivity may be of critical importance when the matrix is impermeable, it may only play a secondary role to fracture orientation and density when the matrix is permeable.

A1.3 Matrix Characteristics

The hydrogeological significance of a fracture system cannot be assessed without reference to the hydrogeological characteristics of the matrix. If the hydraulic conductivity of the fracture system in an aquifer is of the same order of magnitude or less than that of the matrix then the fracture system is unlikely to be hydraulically significant, but if the same fracture system were present in a matrix with a low hydraulic conductivity, such as a series of interbedded shales and thin sandstones, then it is likely to be more hydraulically significant. This section briefly describes the matrix characteristics of clastic sediments and the most significant controls on matrix permeability. It describes the importance of scale dependent variations in matrix hydraulic conductivity and notes the relationships between lithological characteristics of the matrix and the type and nature of fracturing that may develop.

Clastic sediments exhibit a very wide range of hydraulic conductivities. Table A1.1 shows the typical range of hydraulic conductivities and permeabilities for shales and sandstones and unconsolidated sediments including silts, sands and gravels (after Domenico and Schwartz, 1990). Sandstones typically exhibit four or five orders of magnitude variation in hydraulic conductivity, from around 10^{-5} to about 0.5 m/d, and shales around four orders of magnitude variation, from 10^{-8} to 10^{-4} m/d. Porosities of Permo-Triassic sandstones in the BGS aquifer properties core database (Allen *et al.* 1997) typically range from 15 to 30 %, with a mean of 26%, equivalent to saturated bulk densities of 2.40 to 2.15 g/cm^3. The median hydraulic conductivity from the same material in the BGS aquifer properties database is 0.56 m/d.

Table A1.1 Summary of the typical ranges of hydraulic conductivities and permeabilities for shales and sandstones and for unconsolidated sediments including silts, sands and gravels (after Domenico and Schwartz, 1990).

Material	Representative range of hydraulic conductivity (m/d)
Gravel	$3x10^1$ - $3x\ 10^3$
Fine-coarse sand	$2x10^{-2}$ - $5x10^2$
Silt, loess	10^{-4} - 2
Sandstone	$3x10^{-5}$ - $5x10^{-1}$
Shale	$9x10^{-9}$ - $2x\ 10^{-4}$

Matrix hydraulic conductivity and permeability are principally controlled by the distribution of pore-throat sizes and are only poorly related to porosity (pore-throat size distribution is often a function of porosity). These relationships are illustrated in Figure A1.5 which shows the strong correlation between dominant pore-throat size and permeability for samples of St Bees Sandstone from Cumbria (Nirex, 1995). Matrix pore-throat size is controlled by a number of factors including the original size and degree of sorting of the sedimentary grains and post-depositional diagenetic processes, such as sediment compaction, cementation and cement dissolution. The open circles in Figure A1.5 are samples that exhibit cement-dissolution porosity and/or grain dissolution porosity and were originally well sorted coarse-grained sandstones with relatively open packing. The closed circles represent samples that generally exhibit poor sorting, closer packing and relatively high interstitial clay contents. Cement and grain dissolution is absent from these latter samples.

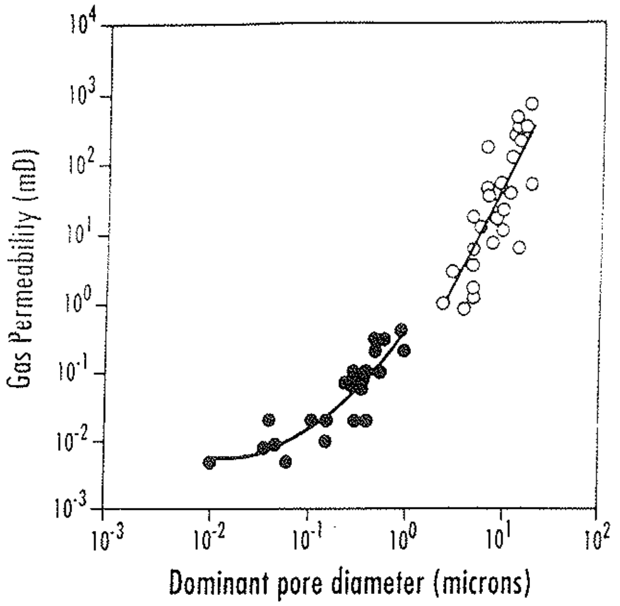


Figure A1.5 **Illustration of the relationship between matrix permeability and pore-throat size (from Nirex 1995). Open circles denote well sorted sandstones that show cement and grain dissolution and closed circles denote samples that show poor grain sorting, high clay contents and no cement or grain dissolution**

A number of fabric features can be recognised in the matrix over a range of scales, and these can be shown to influence the scaling characteristics of the matrix conductivity. Figure A1.6 (after Jensen, Corbett, Pickup and Ringrose 1996) is a schematic illustration of matrix fabrics from the mm to 100's m scale. The smallest regular variations in the matrix fabric are mm to cm thick laminations that form the foresets of false-bedding planes. These features are due to interlamination variations in grain size and/or mineralogy and/or cementation. Cyclic bedding features, composed of numerous laminations, dominate at the cm to m scale and at the largest scale (cms to 100s m) variations in bed characteristics may arise due to systematic variations in the depositional environment of the sediments. Hydraulic conductivity profiles should also show characteristic distributions at different scales as a consequence of the systematic variations in fabric with scale. This is illustrated graphically in Figure A1.6.

The relationship between matrix characteristics and fracture systems is highly complex, however a number of basic observations can be made. Most clastic sequences are both lithologically and mechanically heterogeneous. Fractures preferentially develop in more brittle lithologies in a sedimentary sequence (Lorenz *et al.* 1991), they may change orientation and become refracted through softer more ductile layers and they may pass into zones of diffuse or distributed deformation when the matrix material is highly incompetent. Generally well cemented, low to medium porosity, sandstones are most susceptible to fracturing, whereas high porosity, poorly cemented sandstones are much less susceptible. Uncemented sandstones are unlikely to exhibit pervasive fracturing. Cemented or consolidated shales may fracture, but because of their strong sedimentary fabric are more likely to split along bedding partings, particularly at shallow deths. Soft mudstones are usually unfractured.

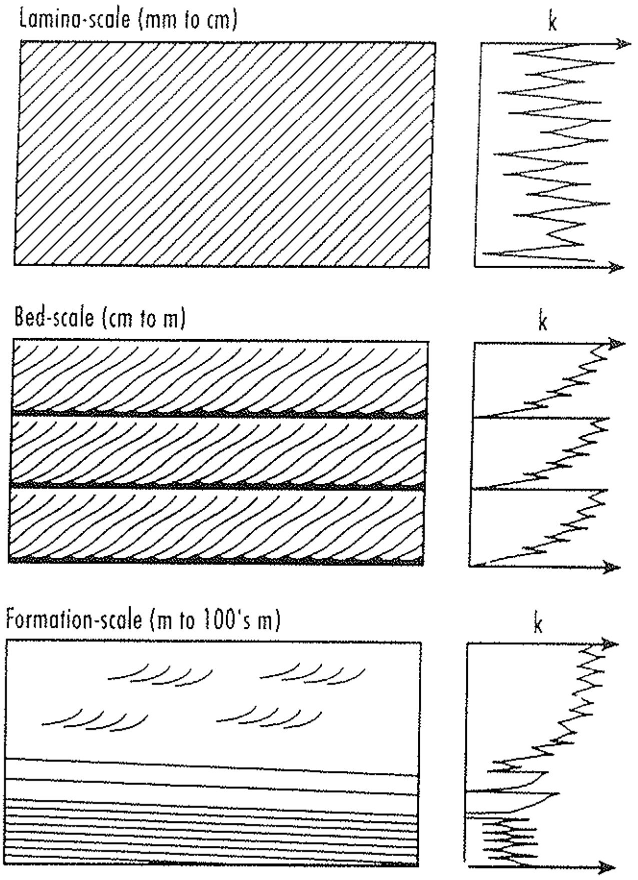


Figure A1.6 **Schematic illustration of matrix fabrics from the mm to 100's m scale. The systematic variation in sedimentary structures at different scales leads to a variation in the character of hydraulic conductivity profiles at different scales as illustrated to the right-hand side of the figure (after Jensen, Corbett, Pickup and Ringrose 1996)**

The distribution of different lithotypes in an aquifer may also play a role in the development and scaling of subsequent fractures at a local scale. Three common facies can be recognised in the Permo-Triassic sandstone aquifer, these are channel deposits, overbank sediments and aeolian sands. The stream or river channel deposits typically consist of localised coarse- to medium-grained moderate- to poorly-sorted sandstones in fining upward cycles that often pass laterally into flaggy shales. The overbank or flood deposits generally consist of laterally extensive fine-grained sands and shales and the aeolian deposits are characteristically coarse well sorted strongly cross-bedded sandstones. Each facies may have characteristic dimensions that may affect the subsequent development of features such as bedding plane partings. In an interbedded series of channel and overbank deposits, although there may be significantly more channel deposits they will be localised and may only be a few tens of metres wide. Whereas the overbank deposits although volumetrically inferior may extend for hundreds of metres. Consequently, bedding plane fractures developed in association with overbank deposits may be more laterally extensive, and hydrogeologically significant, than those associated with channel deposits.

A1.4 Fracture Distributions in Sandstones

Fractures are a ubiquitous feature of consolidated sandstones and are present over a very wide range of scales, from microfractures with lengths and apertures of a few tens of microns, to kilometre scale faults bounding entire sedimentary basins. The purpose of this section is to describe the principal characteristics of fractures that are likely to be present in the Permo-Triassic sandstone aquifer and to focus on features of fracture networks that are thought to be of significance for the hydraulic behaviour of the aquifer. Table A1.2 summarises the range of expected fracture distributions and characteristics in sandstones.

Table A1.2 Summary of range of expected fracture distributions in sandstones

Fracture type	Size (lateral extent)	Aperture	Spacing	Orientation	Comments
Bedding plane fractures	10s m to 100s m	10 µm to 10 cm	cm to 10s m	Generally sub-horizontal	Scale dependent size and spacing. Preferentially developed at shallow depth.
False-bedding (cross-bedding) plane fractures	cm to 10 m proportional to bedding thickness	< 1 mm	mm to cm	Dips up to ca. 30°. Direction records palaeocurrent direction.	Scale dependent size and spacing.
Joints	cm to 10s m	10 µm to 1 mm	cm to 10s m	2-3 conjugate or orthogonal sets at high angle to bedding. Locally orientation affected by faults.	Spacing dependent on bedding thickness. Best developed at shallow depths.
Faults	mm to 10s km	Complex structure of faults/fault zones makes concept of fault aperture inappropriate	mm to km	Any	Scale invariant size, spacing and displacement. No absolute aperture.

A1.4.1 *Bedding plane and false-bedding plane fractures*

There are few published descriptions of the size, spacing, aperture, connectivity and depth of development of bedding plane or false-bedding plane fractures in onshore sandstones. However, order of magnitude estimates of these parameters could be made on a local basis, primarily based on knowledge of the gross sedimentary architecture of the aquifers, *i.e.* bedding thickness and lateral extent of sedimentary facies. Typically, bedding plane fracture spacings may vary from a few centimetres in finely bedded sandstones to tens of metres in massively bedded sandstones. Fracture size, or lateral extent, may vary from a few centimetres to hundreds of metres. In map view smaller bedding plane fractures may be ellipsoidal in shape, but if larger bedding plane fractures abut against high angle fractures, such as faults, then they may be polygonal in shape (see Section 4 for further discussion and conceptual model). Bedding plane fractures may also have large aspect ratios where the bounding features are strongly anisotropic.

Bedding plane fracture apertures are expected to be highly variable and may range from tens of microns to a few centimetres with most apertures in the sub-millimetre to millimetre range. False-bedding plane fractures are expected to be significantly smaller than bedding plane fractures, the spacing and size of the fractures being entirely dependent on the spacing and size of false-bedding planes. Typically their spacing may be expected to be in the millimetre to centimetre range and their length in the centimetre to metre range. False-bedding plane fracture apertures are also expected to be small compared with bedding plane fractures and are likely to be at the sub-millimetre scale. The development of bedding plane fractures may be associated with the removal of overburden and stress relief processes. Consequently, bedding plane fractures may be expected to be both more numerous, more laterally extensive and have larger apertures at relatively shallow depths than at deeper levels. The spacing of bedding plane fractures will be scale dependent and will be a function of the frequency of bedding planes. However, bedding plane fractures may not be present at all bedding surfaces.

Irregular aperture distributions are likely to be a characteristic of individual bedding plane fractures, particularly where the original bedding surfaces are undulatory or non-planar. Evidence, mainly from the rock mechanics literature (Brown and Scholz 1985, Scholz and Aviles 1986, Wong *et al.* 1989, Barton and Zoback 1992), suggests that tectonic fractures exhibit scale independent, or fractal, surface roughness and aperture distributions, *i.e.* that over a number of orders of magnitude (from the micron to tens of centimetre scales) the nature or degree of variability in fracture aperture is independent of the scale of the observation. However, this may not hold for bedding plane fractures. Any flow through bedding plane fractures may be localised due to the original heterogeneity in fracture aperture and sections of the fracture may be preferentially enlarged through feedback processes (for example enhanced dissolution or mechanical abrasion due to higher flow rates and/or larger volumes of water), but this may be a scale dependent phenomena. Because flow may be localised within bedding plane fractures it is important to obtain direct measurements of bedding plane fracture apertures to assess the possible extent of channelled flow.

A1.4.2 *Joints*

Joints are the most commonly observed fractures at surface exposures and they typically form a characteristic pattern of two or three orthogonal or conjugate joint sets where the most extensively developed regional joint set is co-incident with the regional compressive stress direction and perpendicular to the least principal stress (Lorenz *et al.* 1991). Figure A1.7 shows typical relationships between different joint sets and regional folding. There is a continuing debate as to how regional joints may form and propagate (Pollard and Aydin 1988, Lorenz *et al.* 1991), but it is likely that they grow from "flaws", or mechanical heterogeneities, in the rockmass when local stresses at the flaws exceed the tensile strength of the rock. This may happen under a variety of stress conditions and may occur at depths of hundreds or even thousands of metres in sedimentary basins if pore pressures are high enough to significantly reduce the effective pressure. However, joints are most intensively developed near the ground surface due to stress relief (Merin 1992) If the regional stress field is locally disturbed, by pre-existing structures such as faults or folds, then the local joint orientations may also be modified (Rawnsley *et al.* 1992).

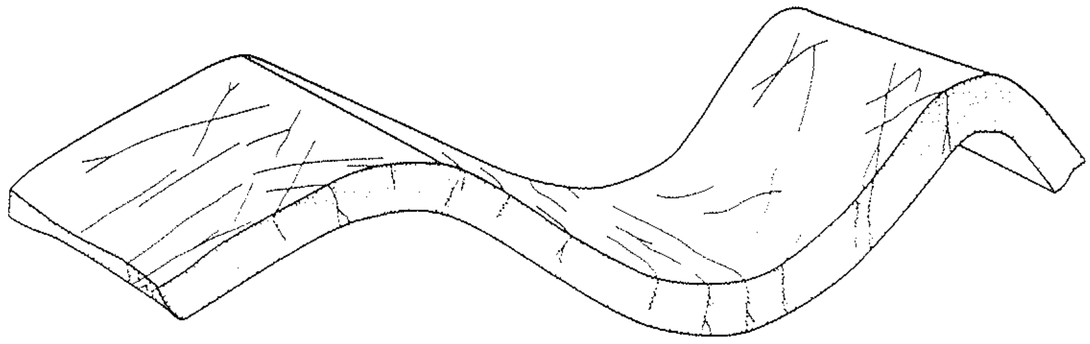


Figure A1.7 Typical relationships between different joint sets and regional folding (after Hobbs, Means and Williams 1976)

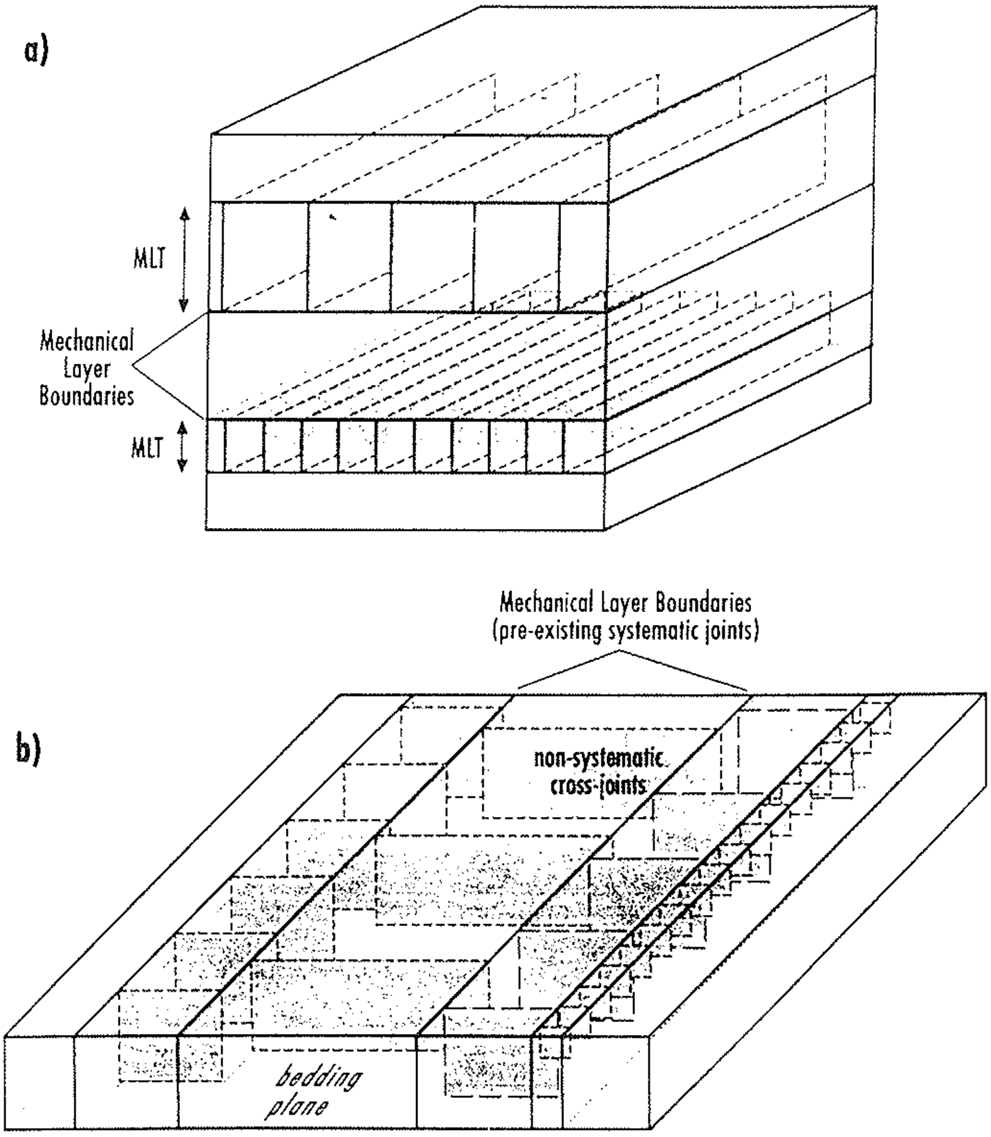


Figure A1.8 Illustration that a.) mean spacing of a single joint set within a bed is proportional to the thickness of the sedimentary layer, and b.) that cross-joints, later second generation joints formed at a high angle to the initial joint set, may also exhibit a mean spacing proportional to the spacing of the initial joint set (after Gross 1993)

Typically joint spacings may vary from centimetres in finely bedded sandstones to tens of metres in massively bedded sandstones and joint size may vary from a few centimetres to a few metres. Joint apertures are expected to be much less variable than bedding plane fracture apertures and are typically in the tens of microns to millimetre range. In poorly cemented or consolidated sandstones it may be difficult to distinguish joints as discrete surfaces with a finite aperture. In well bedded sequences joints are commonly restricted to single beds and terminate against bedding planes or bedding plane fractures and their size distribution is largely controlled by the distribution of bed thicknesses. However, in more massive sandstones, including strongly cross-bedded sandstones, where the mechanical characteristics of individual beds are less homogeneous, joints may be not fully cross-cut beds or may cross-cut more than one bed.

Ladeira and Price (1981), Narr and Suppe (1991) and Bloomfield (1996) have shown that in carbonate sedimentary sequences the mean spacing of joints from a single joint set within a single bed is proportional to the thickness of the sedimentary layer (as illustrated schematically in Figure A1.8). Cross-joints, later second generation joints formed at a high angle to the initial joint set, may also exhibit mean spacings proportional to the spacing of the initial joint set (Gross 1993, Rives *et al.* 1994). If cross-joints are present ladder- or grid-like orthogonal joint systems develop (Figure A1.8). There may also be a similar relationship for well bedded sandstones, although the relationship between joint spacing and bed thickness may be more difficult to identify in poorly consolidated sandstones or massive sandstone beds, particularly where there is cross-bedding.

Joint spacing populations have been described for hard rocks and for sedimentary sequences using a number of distributions, *e.g.* the negative exponential distribution, the log-normal distribution (Rouleau and Gale 1985, Narr and Suppe 1991), the gamma distribution (Huang and Angellier 1989), and the Weibull distribution. Rives *et al.* (1994) have suggested that joint set spacing distributions may evolve within a single bed from an exponential distribution, through a log-normal distribution, to a normal distribution. If a single joint set is sampled then a skewed spacing distribution is commonly obtained and the data can usually be fitted to a log-normal distribution. In addition to stochastic descriptions of joint spacings, geostatistical techniques may be used to investigate the degree of spatial correlation between joints.

A1.4.3 *Faults and fault seal*

Unlike bedding plane fractures and joints, where size and spacing are scale dependent, fault spacing, size and displacement have been shown to be scale invariant (for example, see Gillespie *et al.* 1993 for a comparative study of joint and fault distributions). One of the consequences of scale invariant spacing is that in a given region faults will not show a characteristic size or spacing, rather they will be clustered with many smaller faults near a few larger faults. In addition, the form of the spacing frequency distribution should remain similar regardless of the scale of measurement, the spacing distribution will just be displaced along the spacing axis (this observation may be very useful in extrapolating relatively small-scale field observations to larger areas of the aquifer). However, the degree of clustering and the size of faults may vary between different tectonic regimes within and between different sedimentary basins.

The concept of fault aperture has little meaning. Faults are rarely simple structures and commonly consist of multiple subparallel, often overlapping, fault surfaces containing fault gouge, shale smears or fault breccias (see Figure A1.9 for illustrative examples). Studies of well bedded Chalk in Yorkshire (Childs *et al.* 1996) have shown that normal fault offsets often occur at mechanically weak horizons, for example at the intersection of faults and weak bedding planes or at fault-fault intersections, and are associated with localised zones of intense brecciation and damage to the matrix (Figure A1.9b). These damage zones are areas of increased porosity, and may form tube- or pipe-like structures within the plane of the fault zone. These observations may also apply to well bedded Permo-Triassic sandstones containing variable lithologies such as sandstones and shales.

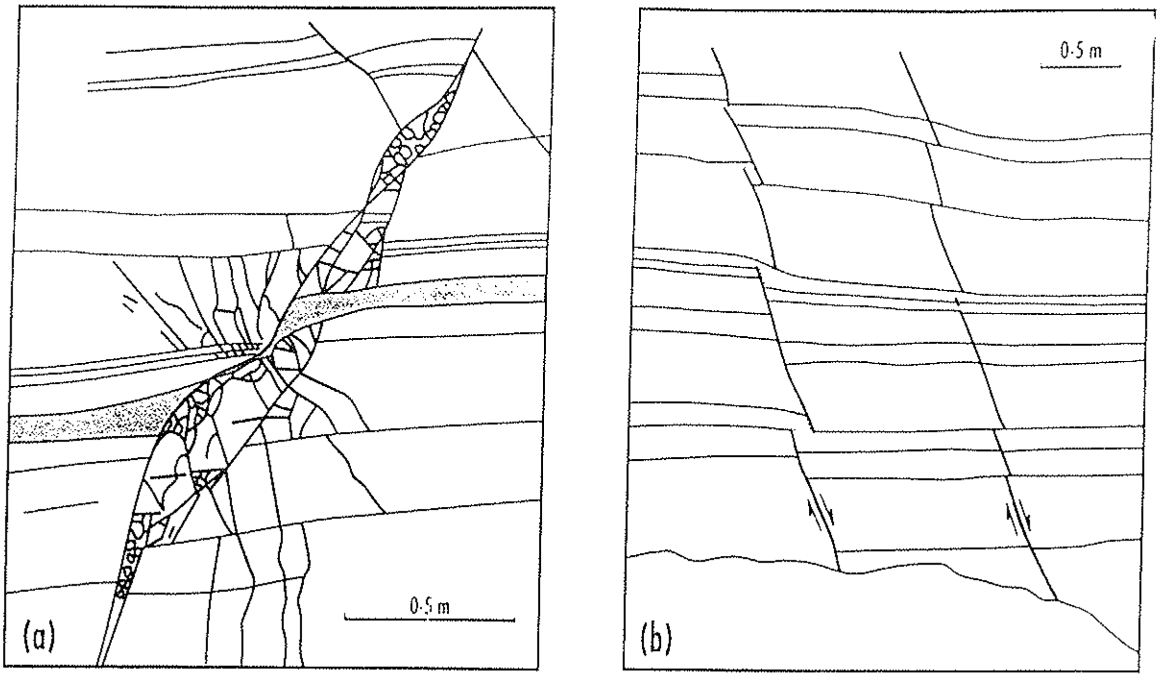


Figure A1.9 **Illustration that faults are rarely simple single surfaces but may consist of a number of smaller segments (a.) and may contain complex damage zones at the junctions of the fault segments (b.). These examples are from the Chalk of Yorkshire (after Childs *et al.* 1996)**

Strongly anisotropic structures develop during faulting, and these features may cause faults to act as baffles to groundwater flow. For example, Randolph and Johnson (1989) studied the Hickory Sandstone aquifer of Texas, a 130 m thick high porosity, quartz sandstone aquifer. The aquifer contains numerous normal and wrench faults of varying displacements. It was found that a good understanding of the detailed geological structure was critical to a proper analysis of the hydrogeological data. Analysis of temporal and spatial variations of water levels in uncased wells showed that discrete faults or fault zones with net displacements of not more than 30 m measurably influenced groundwater flow. On a time scale of several years sustained water-level differences from 3 to 6 m occurred across faults with 30 to 50 m displacements and the hydraulic-head differences appeared to be greater across faults with greater displacements. In addition, water level gradients differed across the faults. In regions of the aquifer bounded entirely by faults with moderate displacements the hydraulic head gradients were much smaller than gradients across regions only partially bounded by faults.

Two principal classes of features associated with faults may contribute to the development of structural and hydraulic anisotropy, these are: deformation of the matrix adjacent to faults - the cataclastic slip zones in Fig A1.3a, and the generation of fault gouges and clay smears (Fig A1.3b) within the plane of the fault. The presence of cataclastic slip zones in the matrix adjacent to a fault can decrease the hydraulic conductivity of the matrix perpendicular to the fault, but increase the hydraulic conductivity parallel to the fault, and generation of fault gouges and clay or shale smears can significantly reduce the hydraulic conductivity perpendicular to the fault.

Cataclastic slip bands, microfracturing, pressure solution and cementation may all be associated with faulting events and can all impart an anisotropic fabric to the matrix. For example, Fowles and Burley (1994) investigated the changes in matrix porosity and permeability of coarse Lower Permian sandstones from north-west England and south-west Scotland near faults with displacements on the metre scale. Core analysis of material taken from profiles across millimetre-wide cataclastic slip bands in the matrix showed that matrix porosity was about 20% away from the slip bands but increased rapidly to about 30% within a zone approximately 25 cm either side of the slip bands, however, in the very centre of the cataclastic slip zone porosity was reduced to 7% (Figure A1.10a). Matrix permeability showed similar trends. Away from the cataclastic slip band the permeability was about 400 mD, within about 25 cm of the slip bands it increased to approximately 2000 mD, but in the very centre of the slip band it was only 3 mD (Figure A1.10b).

The thickness of fault gouge and fault rocks in a fault plane may vary by up to 2 orders of magnitude on a single fault plane (Childs *et al.* 1996). Strongly heterogeneous fault rock distributions are most common on smaller faults and are produced mainly by the destruction of the fault offsets that occur at mechanically weak layers. With increasing displacement on faults shearing leads to more homogeneous fault rocks. As fault rocks may have significantly different porosities and permeabilities with respect to the matrix the potential for the development of hydraulic anisotropy increases for larger faults. Generally, fault rocks may be expected to significantly reduce permeability across the fault, although they may under certain circumstances increase the permeability parallel to the fault (the pipe-like damage zones described above). Mineralisation or cementation of the fault plane may also significantly reduce permeability across the fault.

Faults with larger displacements generally show greater thicknesses of fault rocks. Knott (1994) measured displacements and thicknesses of 55 fault zones in the Permo-Triassic sandstones of north-west England and found that there was a positive correlation between fault displacement and fault zone thickness. Fault displacements ranged from approximately 2 mm to 10 m and fault zone thicknesses ranged from 2 mm to 1 m. It is assumed that the larger the displacement on a fault the greater the potential decrease in permeability across the fault. In addition to larger faults having greater thicknesses of fault rocks than smaller faults, there is also a higher probability of larger faults encountering and displacing shales in a mixed sandstone and shale sequence leading to the formation of shale smears.

There is a significant body of work in the hydrocarbons literature describing the formation of fault-zone seals in mixed sandstone and shale sequences. A number of sophisticated methods have been developed to predict which parts of a fault zone will seal and how impermeable they are (usually expressed in terms of height of hydrocarbon column the seal will support), given the detailed lithostratigraphy adjacent to the fault zone and the displacement gradient along the fault zone. Shearing of relatively ductile shales into the fault surface significantly decreases the permeability perpendicular to the fault zone, and Gibson (1994) has suggested that fault seals formed by shale smears become continuous where the shale content of the section displaced along the fault exceeds 25% (shale smear factor, or ssf, <4).

In summary, faults may be envisaged as hydraulically anisotropic structures. They may contain a core consisting of relatively impermeable gouge and clay smears that will reduce horizontal permeability, and/or pipe-like structures in the plane of the fault that may have increased hydraulic conductivity. The degree to which permeability across the fault is reduced is dependent on the adjacent stratigraphy, specifically the shale content, and the size of the displacement on the fault. In addition, the fault will be surrounded by zones of damaged matrix that may contain anisotropic structures, such as oriented microcracks, or oriented low porosity cataclastic slip bands. These features will generally act to reduce hydraulic conductivity in a direction perpendicular to the fault but that may significantly increase hydraulic conductivity parallel to the fault plane.

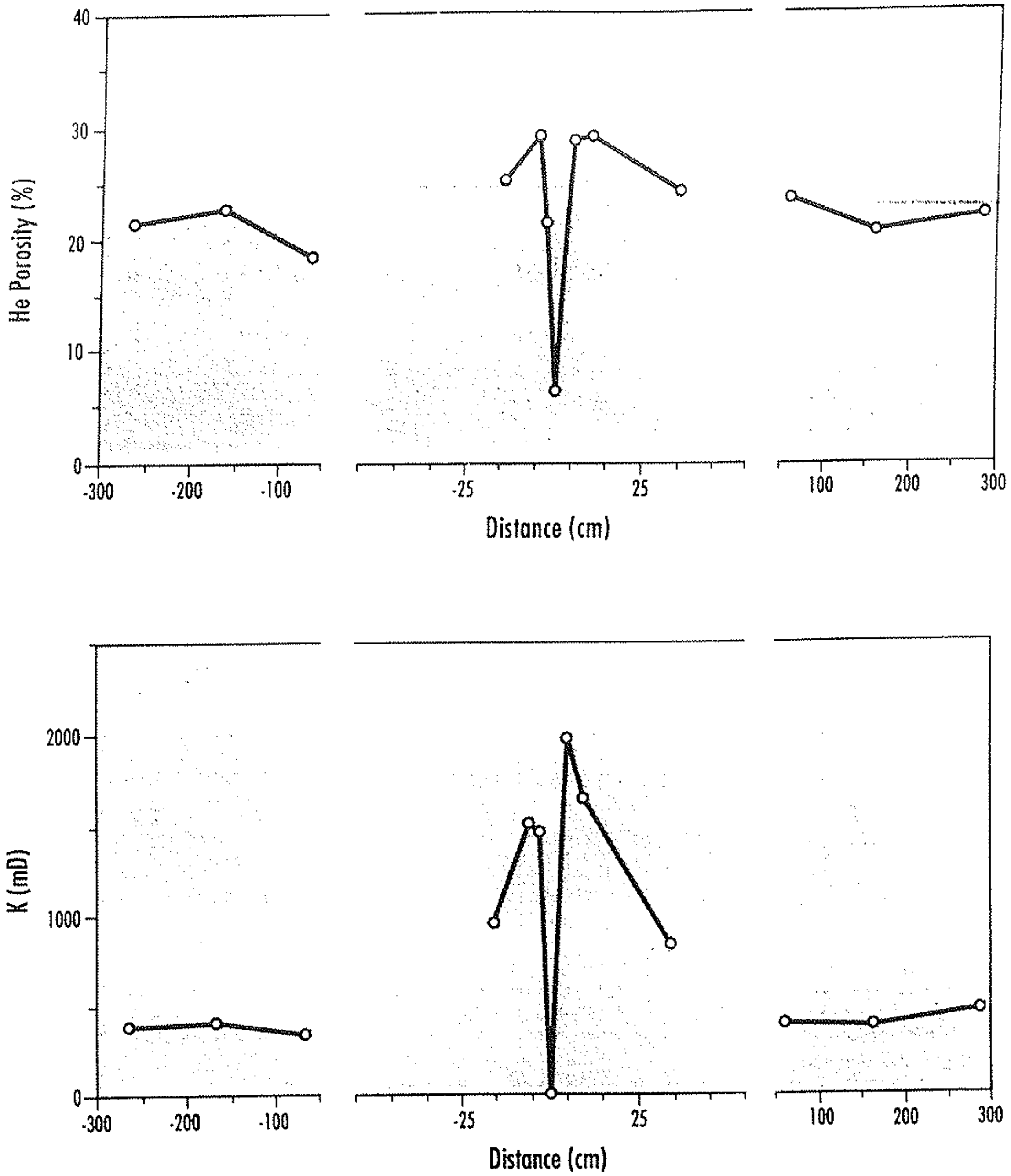


Figure A1.10 Example of variation in a.) matrix porosity, and b.) matrix permeability across a fault in Lower Permian sandstones (after Fowles and Burley 1994)

A1.5 Theory of Fracture Hydraulics

A1.5.1 *Single fracture*

The problem of laminar flow of a viscous incompressible fluid in a fracture has been studied by many workers since the nineteenth century and particularly in the last few decades (e.g. Boussinesq 1868; Snow 1965, 1968; Witherspoon *et al.* 1980, Tsang 1992, Renshaw 1995). For laminar flow between smooth parallel plates the fracture hydraulic conductivity has been shown to be:

$$K = \frac{b^2 \rho g}{12\mu} \tag{1}$$

where K = fracture hydraulic conductivity (LT^{-1})
b = fracture aperture (L)
ρ = fluid density (ML^{-3})
g = acceleration due to gravity (LT^{-2})
μ = dynamic viscosity of fluid ($ML^{-1}T^{-1}$)

since:

$$\nu = \frac{\mu}{\rho}$$

where ν = kinematic viscosity (L^2T^{-1})

then equation (1) may be represented as:

$$K = \frac{b^2 g}{12\nu} \tag{2}$$

The transmissivity of a single fracture is given by:

$$T = Kb \tag{3}$$

Therefore, from equation (2)

$$T = \frac{b^3 g}{12\nu} \tag{4}$$

Flow in an ideal fracture

For steady, isothermal flow in a fracture the flux may be obtained from Darcy's Law to give (for linear flow):

$$Q = -\frac{b^3 g}{12\nu}\left(\frac{W}{L}\right)\Delta H \tag{5}$$

where Q = flow rate in the fracture (L^3T^{-1})
W = fracture width (L)
L = fracture length ($l_2 - l_1$) (L)
ΔH = hydraulic head difference ($H(l_2)-H(l_1)$) over fracture length L (L)

For steady-state radial flow from an injection well the following equation (based on the Thiem equation) applies:

$$Q = -\frac{b^3 g}{12\nu}\left(\frac{2\pi}{\ln r_e / r_w}\right)\Delta H \tag{6}$$

where r_e = outer radius (L)
r_w = wellbore radius (L)
ΔH = hydraulic head difference ($H(r_e) - H(r_w)$) (L)

Equation (4) and (5), and the modified form - equation (6), are both referred to as the 'cubic law' for the hydraulic properties of a fracture. They indicate that the transmissivity and therefore the flow in an ideal fracture is highly dependent on its aperture.

A1.5.2 *Fracture sets*

Snow (1965) noted that for a series of N parallel fractures per unit distance across a rock face equation (2) is modified to give an effective bulk hydraulic conductivity, K_{eff}:

$$K_{eff} = \frac{Nb^3 g}{12\nu} \tag{7}$$

If a cubic system is created by three orthogonal fracture sets then the hydraulic conductivity parallel to any two sets is given by:

$$K_{eff} = \frac{Nb^3 g}{6\nu} \tag{8}$$

A1.5.3 *Implication of the ideal fracture equations for groundwater flow*

For water at 10°C (taken to be groundwater temperature in the UK):
ρ = 999.7 kgm^{-3}
μ = 1.3037×10^{-3} Ns m^{-2}
g = 9.8118 ms^{-2}
(Values taken from Kaye and Laby [1978])

Therefore:

$$\nu = 1.3041 \times 10^{-6}\ m^2s^{-1}$$

and

$$\frac{g}{12\nu} = 5.417 \times 10^{10}\ m^{-1}d^{-1}$$

Thus equation (2) can be represented as

$$K = b^2 \times 5.417 \times 10^{10}$$

where K is in m/d and b is in m; or in more practical units

$$K = b^2 \times 5.417 \times 10^4$$

where K is in m/d and b is in mm. Table A1.3 shows the hydraulic conductivity and transmissivity of a single fracture for a range of apertures:

Table A1.3 Variation of hydraulic conductivity and transmissivity with aperture for a single planar fracture

Fracture aperture (mm)	K (m/d)	T (m^2/d)
0.01	5	1×10^{-4}
0.1	542	0.05
1	5.42×10^4	54.2
2	2.17×10^5	433
5	1.35×10^6	6.7×10^3

A1.5.4 *Effective aperture*

For the parallel plate fracture model there is no ambiguity as to the fracture aperture, it is always a single value, usually denoted as 'b'. However for real fractures the fracture aperture varies enormously and can be described by a fracture aperture density distribution and a correlation length.

From literature on field studies involving tracer tests and hydraulic tests an 'equivalent aperture' value is often derived. However, there appears to be a discrepancy in the literature as to values obtained for the 'equivalent aperture' from the different field study types. This has arisen from an inconsistency in the use of the term for equivalent aperture. Tsang (1992) addresses this problem, and proves that the results in the literature are in fact consistent with each other, with the confusion arising due to the terminology used for the fracture aperture.

Tsang (1992) notes that there are three ways in which the 'equivalent aperture' can be defined:

Mass Balance Aperture

This aperture type derives from tracer test data and the measurement of the volumetric flow rate, Q, the mean residence time of tracer transport, t_w, and the assumption that the area of the single fracture, A, in which the transport takes place is known. This gives:

$$Qt_w = A\delta_m \quad (9)$$

where the mean residence time is determined from the time moment of the measured breakthrough curve. The determination of the mass balance aperture, δ_m, is related to the pore volume of the fracture and can also be related to the arithmetic mean of all the aperture values in the flow paths.

Frictional Loss Aperture

The frictional loss aperture is also derived from tracer test data, and involves the mean residence time, t_w, for tracer transport from the injection point, l_1, to the collection point, l_2, in terms of transport velocity. If the velocity is assumed to be constant from l_1 to l_2 then Darcy's Law can be used with the hydraulic gradient being known across the distance L $(l_2 - l_1)$ and assuming that the real fracture can be represented by a parallel plate one with a frictional loss aperture δ_l rather than 'b' the true parallel plate aperture. This gives:

$$\delta_l = L\left(\frac{12\mu}{\gamma|\Delta H|t_w}\right)^{\frac{1}{2}} \tag{10}$$

where γ is the weight density of the fluid.

This equation must be changed for flow in radially converging or diverging situations and injection-withdrawal dipole flow. For radial flow symmetry (10) becomes:

$$\delta_l = L\left(\frac{6\mu}{\gamma|\Delta H|t_w}\ln\left[\frac{r_1}{r_0}\right]\left(r_1^2 - r_0^2\right)\right)^{\frac{1}{2}} \tag{11}$$

Cubic Law Aperture

The cubic law fracture aperture is the equivalent parallel plate aperture that would allow a certain flow rate at a given pressure drop. For linear flow in a parallel plate with constant aperture b, fracture breadth W and flow path length L, and applying Darcy's Law, equation (5) results, or in the above notation:

$$Q = -\frac{\gamma}{12\mu}\frac{\Delta H}{L}b^3W \tag{12}$$

b then may be replaced by δ_c and solved. For radial flow situations then the above equation can be modified and gives the following expression for the cubic law aperture:

$$\delta_c = \left(\frac{6\mu Q}{\pi\gamma|\Delta H|}\ln\left(\frac{r_1}{r_0}\right)\right)^{\frac{1}{3}} \tag{13}$$

The cubic law aperture is probably the most widely equivalent aperture in the literature, and is often referred to as the hydraulic aperture.

A relationship can now be found to relate all three types of equivalent aperture:

$$\delta_c^3 = \delta_l^2\delta_m \tag{14}$$

and for a given fracture their relative magnitudes may be ranked as follows:

$$\delta_m \geq \delta_c \geq \delta_l \tag{15}$$

Tsang (1992) expands on this and explains that δ_l^2 is proportional to the equivalent permeability for a homogeneous porous medium, and the equivalent permeability for a random 2-D field has the upper bound of an arithmetic mean and lower bound of a harmonic mean. For a linear flow geometry the permeability is well approximated by the geometric mean. δ_m is representative of the arithmetic mean.

The frictional loss and the cubic law apertures both rely on measurements made under a pressure drop in laminar flow. It is interesting to note that the pressure drop is very sensitive to local heterogeneities, and so derived apertures will always be weighted towards the smaller apertures where there is the most resistance to flow and cause the largest head drop.

A1.5.5 *Roughness*

Real fracture surfaces are not smooth parallel plates, but rough surfaces that come into contact with each other at discrete points. The roughness of a fracture can be described mathematically by the aperture density distribution. The roughness of a fracture may also be thought of in terms of small-scale roughness on a large scale undulation (Tsang and Witherspoon, 1983). It is the large scale undulation in the fractures that appears to control the hydraulic properties and the fluid flow characteristics in the fracture.

Fluids appear to take a tortuous path through the fracture and hence deviations from the cubic law are expected. Brown (1987) attempts to quantify the discrepancy between the cubic law predictions and the actual flow through rough walled fractures.

A1.5.6 *Channelling*

Real rock fractures cannot be described as parallel plates, but are rough and have a variable aperture distribution. If each wall of the fracture can be described by an aperture probability density function then the resulting aperture pattern between the two walls will reveal channels simply due to the large variability in apertures. These channels tend to be highly tortuous, intersect each other at various intervals within the fracture and also at discrete locations where fractures intersect each other (Tsang et al., 1991). The majority of fluid flow is observed along selected preferential flow paths comprising less than 30% of the fracture plane (Tsang et al., 1988). The concept of flow channelling has been advocated since the mid 1980s. The idea of flow channelling within fractures was first developed at the Stripa mine in Sweden where the majority of flow from single fractures appeared to come from discrete parts of the fracture.

The hydraulic conductivity of the fractures is controlled by constrictions along the flow paths and is not directly related to the volume of the fracture or average aperture of the fracture. The transport in each channel may be characterised by a mean travel time and a dispersion coefficient of the equivalent 1-D model.

Tsang *et al.* (1991) developed a method for calculating the mean aperture from tracer breakthrough data for the flow channels responsible for the transport. It relies on obtaining data for the individual velocities of tracer arriving at the edge of a fracture. The mean aperture can then be used to calculate the standard deviation of the apertures using the graphical relation of Tsang *et al.* (1988). However, these data are rarely available.

Aperture distributions tend to be modelled using a log-normal distribution, based on the data collected by Snow (1970) which suggested that for many rock types apertures followed a log-normal distribution. Log-normal and truncated gamma distributions of apertures were used by Shapiro and Nicholas (1989) to attempt to predict the form of tracer breakthrough curves, with the gamma distribution fitting the data more closely. Fracture surfaces and therefore apertures have been shown to behave as fractal distributions (Brown 1987) and when fractal surfaces are placed 'parallel' to each other flow channelling properties are observed. As the fracture surfaces are brought close together the validity of the cubic law seems to lessen. Fracture surfaces with higher fractal dimensions appear to behave in more agreement with the cubic law. Odling (1994) supports the view of fractal curves representing fracture surfaces, more specifically self-affine fractals where the asperity height to width ratio decreases with length scale. Some fracture surfaces also show specific wavelength and amplitude characteristics superimposed on the fractal surfaces.

It has been shown by many authors that the channel model provides a sound explanation for the behaviour of real breakthrough curves which cannot be reproduced by parallel plate models (Berkowitz and Braester 1991, Tsang and Tsang 1987).

A1.5.7 *Network modelling*

Network models represent a fractured rock by sets of interconnected finite fractures. This can either be achieved through deterministic modelling where each of the fractures are individually characterised or stochastically modelled where each fracture set has a given distribution for each fracture property and then different realisations of the system are modelled. The networks can be modelled in either 2 or 3-D. The simplest distribution for the fracture parameters is a random or Poisson distribution such as used by Long et al. (1982). Fractal, log-normal and negative exponential distributions are also used frequently to model the variations in fracture trace length, density, orientation and aperture. 2-D models occasionally show channelling properties when apertures are varied, but more frequently the parallel plate assumption is made for the fractures.

The disadvantage with using 2-D models is that they can not adequately describe the fracture network connectivity of the true system. Despite this, 2-D models are more commonly used since computations are simpler (Schwartz et al., 1983; Schwartz et al., 1984; Hestir and Long, 1990). For 3-D systems fractures may be represented either as discs of a finite radius (Long and Witherspoon, 1985; Charlaix et al., 1987; Tsang et al., 1988; Cacas et al., 1990) or by flat planes of finite dimensions (Wilke et al., 1985).