BRITISH GEOLOGICAL SURVEY
Natural Environment Research Council

TECHNICAL REPORT WD/99/13
Hydrogeology Series

Technical Report WD/99/13

FRACFLOW – Geological State-of-the Art Review

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This report was prepared for
European Union IVth Framework

Bibliographic Reference

Bloomfield J P 1999
FRACFLOW – Geological
State-of-the-Art Review
British Geological Survey Report WD/99/13

British Geological Survey Keyworth, Nottinghamshire

BRITISH GEOLOGICAL SURVEY

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FRACFLOW – Geological State-of-the-Art Review

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CLIENT European Union IVth Framework	CLIENT REPORT #
	BGS REPORT# WD/99/13
	CLIENT CONTRACT REF
	BGS PROJECT CODE 80DGD10
	CLASSIFICATION Open

	SIGNATURE	DATE		SIGNATURE	DATE
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Layout checked by	C Sharratt	14/9/99	Assistant Director clearance (if reqd)		

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SUMMARY

This review describes our current understanding of the geological factors that control contaminant transport in the Chalk of Europe. It includes a description of pore-space and fracturing styles within the Chalk aquifer, a discussion of climatic and regional impacts on fracture distributions and style, and a discussion of fracture fills and fracture surface characteristics as they effect physical contaminant migration processes. Some of the more important techniques for Chalk rock mass characterisation in the laboratory and field are also described.

The Chalk has been idealised as a dual porosity aquifer where the fractures provide the pathways for flow and the porosity provides the storage. When a well is pumped flow occurs through the fractures, and the resulting head reduction causes water to drain from the adjacent matrix. Although the Chalk may locally behave in this manner, in general, the response to pumping is more complex. In reality the Chalk is a multi-porosity aquifer, with a range of fracture apertures and matrix pore sizes.

Five components of porosity can be identified in the Chalk. These are,

- Matrix porosity
- Fracture porosity
- Enlarged fracture porosity
- Fracture fill porosity, and
- Modified matrix porosity associated with transmissive fractures

Due to their relatively large apertures, it is the preferentially enlarged component of the fracture porosity that provides the principal path for rapid flow of water and transport of pollutants. The detailed structure of this component of the fracture network (including fracture fills and the modified matrix porosity near the flowing features) affects the extent to which contaminants will be retarded or attenuated. Chemical and microbiological processes may also act to retard or degrade contaminants along these pathways. The unenlarged fracture porosity and smaller fractures are thought to contribute to the specific yield and drainage. Consequently, an understanding of this component of the fracture porosity is important for resource modelling. Pore waters are held essentially immobile in the matrix and do not contribute to flow. However, diffusion of contaminants into the chalk matrix (and subsequent diffusion out of the matrix) is an important process that will prolong the persistence of non-degradable contaminants.

Modification of matrix porosity associated with transmissive fractures may effect the potential for diffusive exchange between fracture and pore waters. The physical properties of fracture surfaces, fracture fills and the matrix adjacent to fractures is expected to be dependent on the extent to which the fracture network has been subject to freshwater circulation, the nature of any cover deposits, and (particularly for shallow fractures) the nature of recent and contemporary weathering. It is therefore reasonable to expect systematic differences between fracture surfaces and fracture fills developed in the Chalk in the relatively humid conditions of north-west Europe and the relatively arid conditions of central and southern Israel where Eocene chalks outcrop. However, little is know about this potentially important aspect of fracturing in the Chalk.

Features of the fracture network in the Chalk that are thought to be of significance for flow and rapid transport of contaminants include, enlarged bedding fractures, faults and fault zones, multi-layer joints, and intersections between prominent fracture sets.

- *Enlarged bedding fractures.* These are often, but not necessarily, associated with sedimentologically controlled features such as flint bands, marls or hardgrounds, or are associated with surfaces where there has been some shear displacement (often associated with marls).

- *Faults and fault zones.* Dilational zones between en-echelon faults may form localised zones of enhanced hydraulic conductivity. Dilational zones and zones of increased fracturing may be found between pairs of extensional faults or fault zones. However, faults may also act as barriers where groundwater flow is perpendicular to the strike of the fault or fault zone.

- *Multi-layer joints.* These may act as pathways for rapid sub-vertical groundwater movement and transport.

- *Intersection between prominent fracture sets.* Intersections between bedding fractures and high angle fracture sets will form linear features in the plane of bedding. Intersections are also possible between two high angle fracture sets. Where faults intersect weaker bedding planes a zone of damage may preferentially develop and flow may be localised within this feature. Fracture intersection directions will be most hydrogeologically significant where they are parallel or sub-parallel to the local or regional hydraulic gradient.

Five important areas have been identified where there is still significant uncertainty regarding fracture porosity. They are as follows

- Fracture connectivity and fracture porosity at the intersection of fracture sets.

- Geometry of preferentially enlarged fracture sub-networks.

- Aperture distributions along connected, preferentially enlarged fracture sub-networks.

- Characteristics of modified matrix porosity adjacent to hydraulically significant fractures.

- Fracture porosity in the shallow weathered zone of the aquifer.

In addition, a detailed understanding of porosity modification processes in the Chalk would enable the generation of more realistic synthetic data sets for use in flow and contaminant transport models in the absence of good field data. Three particular areas have been identified as being important. They are as follows

- Processes associated with the development of preferentially enlarged fracture sub-networks.

- Processes associated with cementation of the Chalk matrix.

- Processes associated with weathering and fracture formation near the ground surface.

1. INTRODUCTION

FRACFLOW is a project funded by the European Commission under the Environment and Climate 1994–1998 Programme (4th Framework Programme). The full project title is 'Contaminant transport, monitoring techniques, and remediation strategies in cross European fractured Chalk'. Partners in the project are the Geological Survey of Denmark (GEUS), Ben Gurion-University of the Negev (Israel), the British Geological Survey (BGS), Karlsruhe University (Germany) and the Hebrew University of Jerusalem (Israel).

The project is a three-year study, initiated in December 1997, with two overall objectives:

- to characterise flux and transport of organic and inorganic contaminants through fractured Chalk systems in Europe, and
- to identify generic contaminant monitoring and remediation strategies for various contaminant and hydrogeological scenarios in fractured Chalk across Europe.

These objectives are to be achieved by using a range of hydrogeological, geochemical, biological and petrophysical techniques at laboratory and field scale. Data on contaminant transport, storage, and degradation will be obtained and integrated in a quantitative manner, and will be used to describe contaminant pathways and rates of transport and degradation in fractured Chalk aquifers and aquitards in Europe. Data and experience from different regions and climates will be evaluated in order to make the results applicable to both humid and arid regions. These data will be assessed to provide recommendations for contaminant monitoring techniques and suggest approaches to remediation at contaminated Chalk sites.

As part of the study, two polluted sites will be investigated in the UK, at Tilmanstone in Kent and at the Cambridgeshire research site, and two field sites will be used in Denmark at Sigerslev Quarry and the Drastrup test site. Only one of the Danish sites, Drastrup, is polluted. Analytical, experimental and model results will be included in the evaluation of the climatic and regional impacts on contaminant hydrogeology at each site.

This review forms part of the initiation phase of the study, and is one in a series of six state-of-the-art reviews covering geology, hydrogeology, hydrogeochemistry, microbiology, modelling and field applications (contaminant monitoring and remediation).

This review describes our current understanding of the geological factors that control contaminant transport in the Chalk of Europe. It includes a description of pore-space within the Chalk aquifer, fracturing styles and characterisation in the laboratory and field, climatic and regional impacts on fracture distributions and style, and a discussion of fracture fills and fracture surface characterisation as they effect physical contaminant migration processes.

The other five state-of-the-art reviews are concerned with:

- The hydrogeology of the Chalk. Specifically, flux and transport distributions in 'active' fractures and the permeability of the matrix and fracture fills.
- The geochemistry of the Chalk, and particularly the potential impact on contaminant retardation and sorbtion.
- Chalk microbiology and particularly the potential for microbiologically mediated retardation or degradation of contaminants in the Chalk.

- The utility of different techniques (such as deterministic, stochastic and mixing cell models) for modelling contaminant transport in the Chalk and in identifying the most appropriate monitoring and remediation strategies at contaminated sites on the Chalk.
- Monitoring and remediation strategies at the operational level.

2.1 Scope and Aims of this 'State-of-the-Art' Review

This 'state-of-the-art' review has four main aims. They are as follows:

(i) to review matrix pore geometry and the geometry of porosity associated with fracture fills,

(ii) to analyse our current understanding of the distribution of fractures in the Chalk over a range of scales, and to review the methodologies for characterising fracture networks in the field and laboratory,

(iii) to assess the climatic and regional impacts on fracture distributions and characteristics,

(iv) to briefly review the implications for site monitoring and remediation of contaminant transport in the chalk, and more specifically, to identify the areas of most significant uncertainty related to contaminant transport in fractured Chalk.

The review has the following structure. After some introductory comments on porosity in the Chalk, there is a review of characteristic features of fracture distributions and fracture network architecture in sedimentary aquifers such as the Chalk. This section includes a note on definitions of fracture terminology used in this report and throughout the project. There is a brief review of the climatic and regional impacts on fractures distributions and characteristics. Techniques for fracture characterisation in the field and laboratory are then reviewed and assessed. The state-of-the-art review is concluded with a brief section outlining some of the implications of fracturing for contaminant transport, site monitoring, and remediation, and the areas of most significant uncertainty related to fracture characterisation and rapid contaminant transport in the Chalk.

3. WHAT ARE THE CHARACTERISTIC FEATURES OF POROSITY IN THE CHALK?

The Chalk has been idealised as a dual porosity aquifer. This is schematically illustrated in **Figure 1** (after Price et al. 1993). As Price et al. (1993) note, in classic dual-porosity aquifers the fractures provide the pathways for flow and the porosity provides the storage. When a well is pumped flow occurs through the fractures, and the resulting head reduction in the fractures causes water to drain from the adjacent matrix. Although the Chalk may locally behave in this manner, in general, the response to pumping is more complex. This is because in reality the Chalk is a multi-porosity aquifer, with a range of fracture apertures and matrix pore sizes. To understand the response of the aquifer to hydraulic stresses and to understand the movement of contaminants it is necessary to develop more realistic conceptual and numerical models of the pore space in the Chalk. This section of the review describes the principal features of different components of porosity in the Chalk.

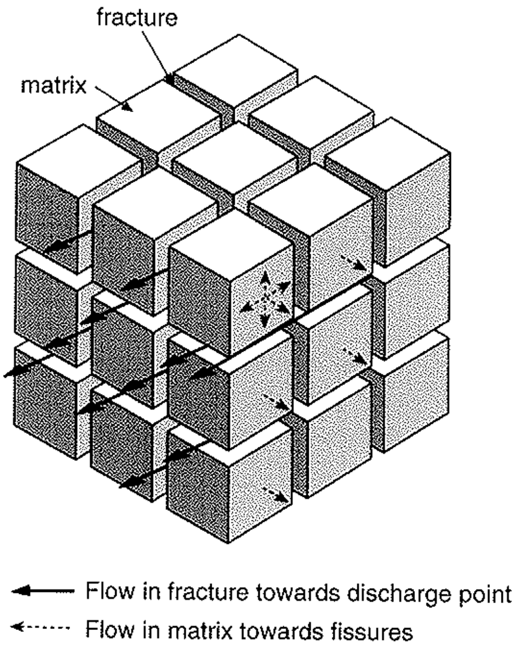


Figure 1. **Schematic illustration of an idealised dual-porosity aquifer such as the Chalk (after Price et al. 1993).**

3.1 Matrix Porosity

The Chalk is a microporous fractured aquifer (Price et al. 1993). It typically has a matrix porosity of about 30 to 40%, but porosity may vary significantly. For example, in France porosity values are 30 to 45% in Artois-Picardy, 23 to 43% in Normandy, 37 to 44% in Champagne and 15 to 40% in Touraine, with values varying according to sedimentary facies (Crampon et al. 1993). In onshore chalks in the UK, matrix porosity has been reported in the range 3.3 to 55.5% with a mean of 34% (Bloomfield et al. 1995). Low matrix porosities are usually associated with hardgrounds or nodular chalks and with chalks that have been buried relatively deeply. For example van Rooijen (1993) notes that in hard bands in the Maastricht Formation of Holland porosity values may be as low as 8% due to the high degree of cementation. **Box 1** describes the primary sedimentary controls on porosity in the Chalk. A characteristic feature of matrix porosity profiles in boreholes is the general reduction in porosity with depth below ground level (see for example the porosity profile shown in **Box 2**). This is because, at the macroscopic scale, matrix porosity predominantly reflects the maximum burial depth of the sediment (Bloomfield et al. 1995).

Chalk pore-throat sizes are typically in the range 0.5 to 1 microns (Price et al. 1976; ENPC 1989; Crampon et al. 1993) and are often essentially unimodal, although some lithologies show a broader range of pore-throat sizes and the pore-size distribution may be modified significantly by weathering. **Figure 2** gives some examples of pore-throat size distributions for a range of Cretaceous and Eocene Chalks from Europe and Israel.

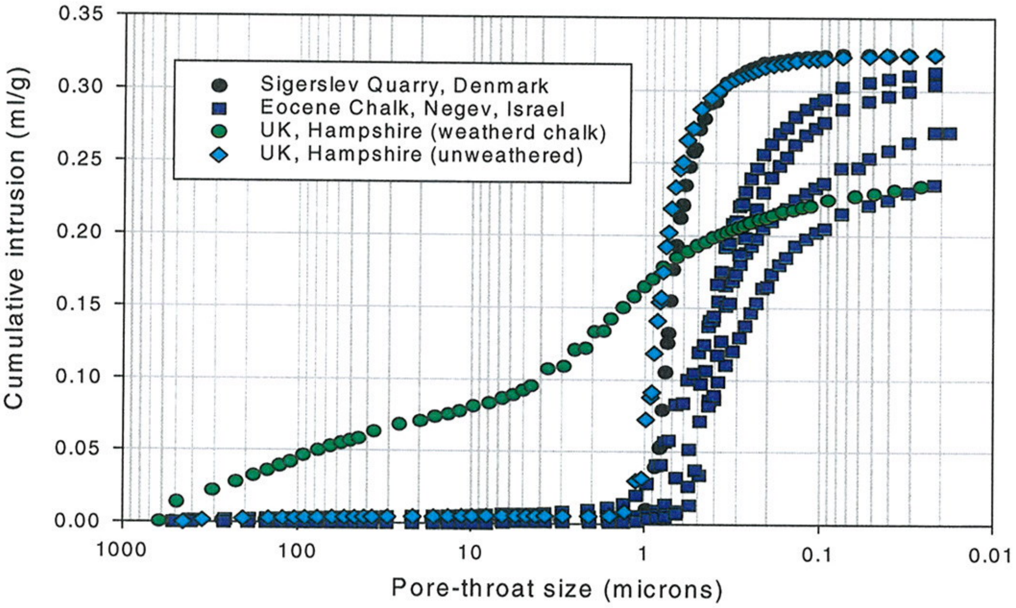


Figure 2. **Some examples of pore-throat size distributions from the Chalk of Europe and Israel.**

The pore-throat size distributions for the sample from Sigerslev Quarry and for the unweathered Chalk from UK are characteristic of much of the Chalk of north-west Europe. They show a limited range of pore-throat sizes, with dominant pore throat-sizes in the range 0.5 to 1.0 micron. The Eocene Chalk samples from Israel show a slightly broader pore-throat size distribution with smaller dominant pore-throat sizes. This is a reflection of the different sedimentological and diagenetic histories. The Eocene chalks are less pure than the northern European chalks and contain variable amounts of siliceous cements, zeolites and clays. The weathered chalk from the UK was obtained from about one metre below the base of the soil zone. Recent weathering processes have caused the original sedimentary fabric to be destroyed, and have resulted in a very broad pore-throat size range.

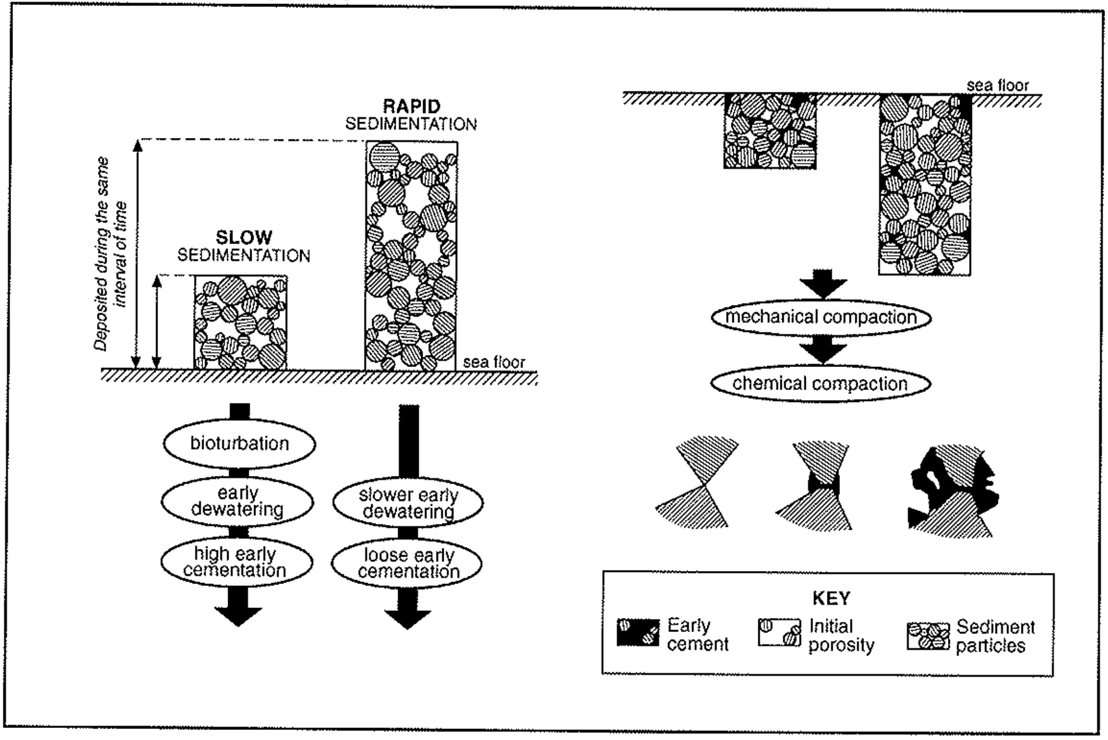
Matrix porosity and pore-throat size distributions of unweathered Chalk are controlled by lithological factors such as primary sedimentary characteristics and the nature and degree of diagenesis. However, Figure 2 shows that the pore-size distributions of very weathered chalks may be modified significantly. Such modifications may have important consequences for recharge and contaminant transport through the unsaturated zone. To date the physical characteristics of the unsaturated zone of the Chalk have not been investigated systematically.

The Chalk has historically been considered a relatively uniform rock type by hydrogeologists, but studies of chalk hydrocarbon reservoirs (Scholle 1977; D'Heur 1984; Clausen et al. 1990; D'Heur 1993) have demonstrated the importance of variations in primary sedimentation and diagenetic history on matrix porosity characteristics in the Chalk. These controls are briefly discussed in **Boxs 1** and **2**. The microporous nature of the Chalk matrix has implications for the hydraulic characteristics of the aquifer. It is generally accepted that pores with diameters less than 10 microns are unlikely to drain under gravity (Price et al. 1976), that water will be held in these pores and consequently that not more than three per cent of chalk pores are thought to contribute to useful storage. This is equivalent to about one percent of bulk volume. It is not clear exactly how chalk drains *in-situ*. It is probably a combination of drainage of fractures and macropores (pores >10 microns). However, Price et al. 1976 note that drainable macropore porosity is of the same order as typical values of Chalk specific yield as measured in laboratory centrifuge tests. Elastic storage may also effect specific yield in the Chalk.

However, because of the highly interconnected nature of porosity in the Chalk, even though the water in the matrix is effectively immobile transport of contaminants and other solutes may take place by molecular diffusion (Barker 1993). Diffusion of contaminants into the matrix of the chalk is an important process. It will act to prolong the persistence of non-degradable contaminants and so hinder clean-up operations. However, it may also lead to significant retardation of contaminants, and

Box 1. Primary sedimentary controls on the porosity of the Chalk matrix

Work on the hydrocarbon reservoirs the Chalk of the North Sea has shown the importance of sedimentary facies in controlling matrix porosity and particularly in preserving high porosities (D'Heur, 1993). Relatively high deposition rates appear to create more open frameworks and are often associated with lower clay contents. These deposits are also less susceptible to biogenetic re-working and an associated reduction in porosity. If these deposits become cemented at grain-grain contact points at an early stage then a rigid framework is created that is relatively resistant to later compaction. Conversely, slower sedimentation, higher rates of bioturbation, and relatively high rates of early cementation contribute to the formation of less porous chalks, such as nodular chalks and chalk hardgrounds. Because they are less porous and consequently harder, hardgrounds may be more susceptible to fracturing and they may act to localise groundwater flow, e.g. the Melbourn Rock, UK (Mortimore, 1993). The figure below (after D'Heur, 1993) is a schematic illustration of the effect of sedimentation rate on matrix porosity.



it may increase the likelihood of them coming into contact with sorbtion sites on clay minerals and organic carbon disseminated in the matrix (Foster 1993).

Due to the small pore-throat size of the matrix, most of the flow of water in the Chalk takes place through the fracture porosity. The following section introduces the concept of fracture porosity in the Chalk, while Section 3 deals with the characteristic features of fractures in the Chalk in more detail.

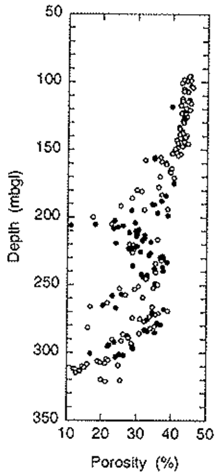
3.2 Fracture Porosity

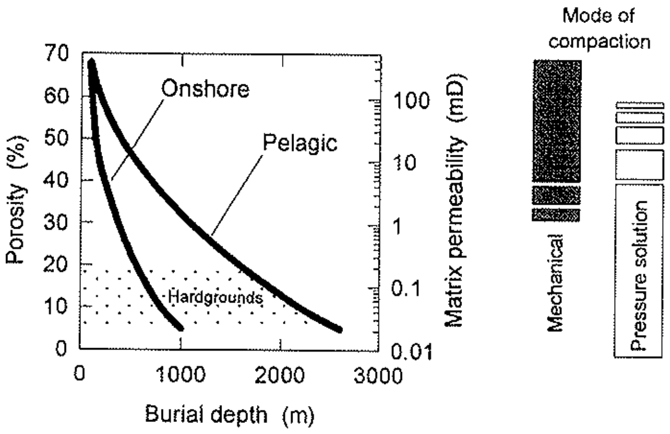
In contrast to the matrix porosity, fracture porosity contributes only a few percent to the total porosity. Fracture apertures are typically up to a few millimetres in width, and typical fracture spacings are in the centimetre to metre range. Because fracture apertures are generally significantly greater than

Box 2. Diagenetic controls on the porosity of the Chalk matrix

There are two principal diagenetic processes that act to modify the pore structure of carbonate sediments as they are buried following sedimentation. These are *mechanical compaction*, the physical reorganisation of individual bioclastic fragments of the Chalk matrix into a progressively denser configuration, and *pressure solution* or *chemical compaction*. The latter entails the reduction of matrix porosity through dissolution and reprecipitation of minerals under conditions of non-hydrostatic stress. Mechanical compaction progresses with increased overburden and predominates during the early stages of burial diagenesis. But as porosity is reduced below about 40 to 35% an increasingly strong grain-supported fabric develops, mechanical grain reorientation becomes more difficult and pressure solution compaction then becomes the primary mechanism for porosity reduction. During pressure solution, carbonate minerals pass into solution at grain-grain contacts to be precipitated at sites of relatively low stress. Pressure solution is particularly sensitive to the chemical environment, and in the Chalk it is enhanced if the connate waters have been flushed with relatively fresh Mg-poor waters (Scholle 1977). Relatively high clay contents may enhance the development of pressure solution and well-developed marl seams and stylolites are an indication that chemical compaction has occurred.

The figure below (left) illustrates a matrix porosity profile from the Chalk of the London Basin (after Bloomfield, 1997). Above about 150 m porosity is relatively high and constant and has only been affected by mechanical compaction, below 150 m, it is much more variable with occasional very low porosities and marl seams and stylolites are present (closed symbols denote samples with marl seams or stylolites). In this depth interval porosity has been variably affected by pressure solution. The effect of a change in the dominant mode of diagenetic compaction as a function of type water chemistries is schematically illustrated in the right hand figure (after Scholle, 1977). The porosity profile was inferred to have been established under an onshore regime but prior to uplift of the Chalk. Once uplifted the inherited pore structure dominated the recent hydrogeological evolution of the aquifer. From the porosity profile, and on the basis of pore water chemistry, (Bloomfield, 1997) inferred that the circulation of relatively fresh groundwater is restricted to the upper interval where pressure solution compaction was absent.





typical matrix pore-throat sizes, they contribute the largest component of specific yield, control the transmissivity of the aquifer, and consequently, are an important factor in the movement of contaminants in the aquifer. As Crampon et al. (1993) have noted, the Chalk is only an aquifer because it contains a network of fractures produced by tectonism and modified by physio-chemical processes.

Schematically, the chalk can be idealised as a dual-porosity aquifer, as illustrated in **Figure 1**. If fractures were present as a regular array with constant apertures it would be possible to calculate hydraulic conductivity from fracture spacing and aperture, **Figure 3**. However, it is known that the Chalk is far from an idealised dual-porosity aquifer. In nature, fracture size, spacing and aperture are distributed parameters and there may be significant variability in the degree and nature of the connectivity between different fracture sets over a range of scales (due to the many geological and hydrogeological processes that led to the development of the aquifer). As a consequence, the lengths over which fractures are connected and the distribution of fracture apertures along these connected paths are highly variable. This has significant implications for contaminant transport. For flow through parallel-sided fractures, transmissivity is given by the so-called 'cubic law' where transmissivity is proportional to the aperture cubed (Barker 1993). Consequently, flow and contaminant transport rates will be highly sensitive to the aperture distribution in the connected fractures.

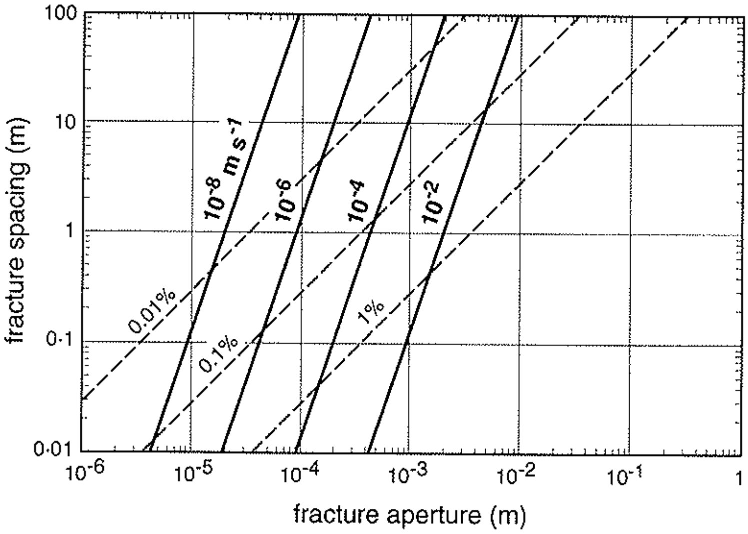


Figure 3. **Graph illustrating the relationship between fracture spacing, aperture, porosity and hydraulic conductivity assuming an idealised fracture network consisting of three orthogonal fracture sets where each fracture is smooth-walled and filled with water at 10 degrees C (after Price et al. 1993).**

Price (1987) refers to the porosity associated with tectonic fracturing as the 'primary-fissure' component of fracture porosity. Superimposed on the heterogeneity imparted by natural fracturing processes, fracture pore space may be modified extensively by physio-chemical processes leading to the development of preferentially enlarged sub-networks. Price (1987) refers to the porosity associated with these enlarged fractures as the 'secondary-fissure' component of fracture porosity. These preferentially enlarged fractures, may provide most of the inflow into boreholes or adits (see, for example, Figure 1.5 in Downing et al. 1993). Locally, such enlargement of components of the fracture network may lead to the development of sub-karstic and karstic features (Crampon et al., 1993; van Rooijen, 1993).

Identification of characteristic features of the sub-network of preferentially enlarged fractures, and the ability to predict the spatial distribution of enlarged fractures are important goals for the study of flow and transport in the Chalk aquifer. This is because the sub-network of preferentially enlarged fractures provides the pathway for the largest and fastest flows in the aquifer.

The processes that lead to the development of these preferentially enlarged fractures and the hydrogeological scenarios or settings that lead to their development are still poorly understood. However, their formation is thought to be intimately related to the hydraulic and hydrogeochemical evolution of the aquifer. The processes associated with fracture enlargement in the Chalk may include

- dissolution of the fracture wall
- mechanical plucking of material from fracture walls, and
- abrasion of fracture walls by transported material

Dissolution may predominate in the 'humid' regions of north-west Europe where there is relatively high recharge, plucking and mechanical wear may predominate in the unsaturated zone in arid regions, such as Israel, that are prone to large irregular recharge events (Weisbrod, Nativ et al. 1998). All of these processes may be affected significantly by the local geochemical environment and by microbiological activity on the surface of the fractures. **Box 3** briefly describes some of the processes and hydrogeological scenarios that may be associated with the development of preferentially enlarged fractures, particularly in humid regions, and **Box 4** introduces some models that have been used to investigate the preferential growth of fractures in aquifers.

3.3 Fracture Fill Porosity

Fractures in the Chalk may contain a variety of filling materials. These will reduce the total fracture porosity and modify fracture aperture size range. In some fractures the porosity may be totally replaced by space-filling cement, usually calcite, but also flint. Fracture fills will reduce the transmissivity of the fracture and will potentially increase the capillarity of a fracture by reducing the effective or dominant pore size if they are not impermeable. Fills may include carbonate, silica or gypsum cements, authigenic clays, or clays and other siliclastic material brought in by groundwater circulation or recharge events (Shand and Bloomfield 1995).

Within a given region there may be systematic correlations between different types of fracture fill and different fracture sets, and fracture fills may be an important fracture mapping tool. For example, the distribution of authigenic clay drapes precipitated out of solution or suspension onto fracture surfaces could indicate which fracture sets were open and transmissive during a phase of groundwater mixing or flushing. The distribution of Palaeogene clays and sands washed into parts of the fracture network from overlying deposits would show which fractures were open and transmissive during a period of recharge. However, to date there have been no systematic surveys of different types of fracture fills in the Chalk, and there has been no systematic assessment of their potential implications for contaminant transport.

Box 3. Processes and hydrogeological scenarios associated with the development of preferentially enlarged fractures in the Chalk under humid conditions

Dissolution

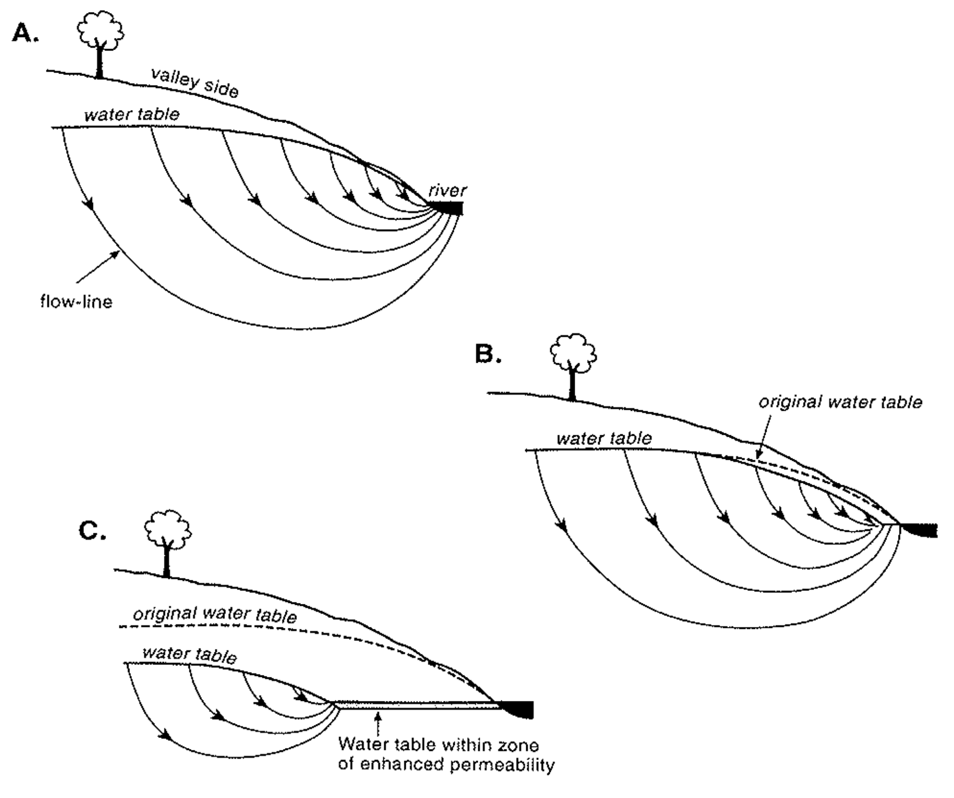
Dissolution is thought to be the principal process of fracture enlargement in the Chalk in NW Europe. However, present-day recharge is essentially fully saturated by the time it has passed through the soil zone (Edmunds 1993), thus limiting the potential for significant present-day dissolution. It has been suggested that much of the development of the enlarged fractures occurred during periglacial episodes when recharge waters were relatively cool and more chemically aggressive with respect to contemporary recharge (Younger 1989). Enlarged fractures have also been recognised beneath the margins of Palaeogene cover (MacDonald 1998), probably resulting from acidic runoff/recharge entering the aquifer. Crampon (1993) and van Rooijen (1993) have described the formation of karst and sub-karstic features from the Chalk of France and Holland. van Rooijen (1993) notes that solution appears primarily in the zone of water table fluctuation along pre-existing fractures.

Other factors

Mechanical weathering and biologically mediated geochemical processes may also be significant factors over geological time-scales and may contribute to the enlargement of shallow fractures. However, to date these factors have not been investigated systematically.

Topographically controlled concentration of flow

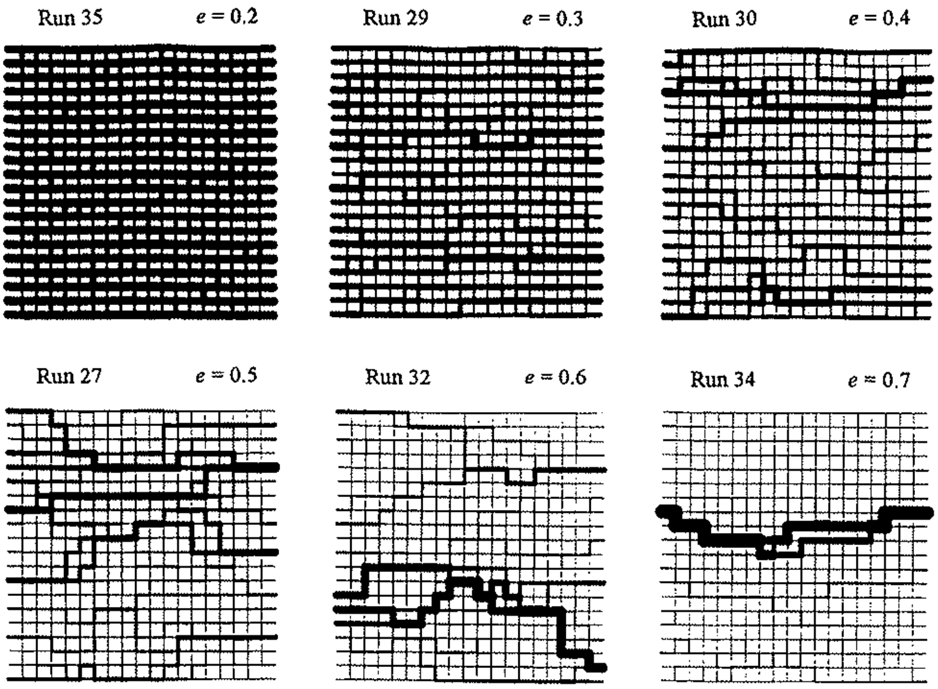
A number of hydrogeological scenarios have been identified that may be associated with the development of preferentially enlarged fractures, regardless of the detailed processes involved. All are based on the concept that fracture enlargement is most pronounced in parts of the aquifer where there is a concentration of groundwater flow. For example, concentration of flow to stable discharge points following the last glaciation is an important control on localised enlargement of parts of the fracture network (Price, 1987; Lloyd,1990; Lloyd, 1993; Price, 1993). In addition, flow may be concentrated as a result of topographic relief or due to thinning of cover rocks. This is illustrated schematically below (after Price 1987).



Box 4. Modelling fracture growth.

There have been numerous geochemical modelling studies of the transport of reactive solutes in fracture networks, and many of these studies have modelled the enlargement of fractures or fracture networks in carbonate rocks by dissolution. Dijk and Berkowitz (1998) and Siemers and Dreybrodt (1998) provide good overviews of studies of carbonate dissolution. A common approach is to specify a mass balance where the rate of fracture enlargement is taken to be proportional to the product of the flux in the fracture and the carbonate dissolution rate. Under laminar flow conditions the flux in the fracture is assumed to be proportional to the cube of the fracture aperture. The rate of dissolution is proportional to a reaction rate co-efficient, solute concentration in the flowing fracture, and to fracture geometry.

However, these models are generally limited to specific hydraulic scenarios or to specific dissolution rate laws dependent on assumed calcium concentrations in the flowing fracture. Bloomfield and Barker (1999) have developed a generic, processes-independent, model of porosity development, and have been able to generate evolved fracture aperture arrays that mimic the geometries of enlarged fracture systems in the Chalk. In the figure below six evolved fracture aperture arrays are shown. In the model the aperture growth rate is equal to q^e , where q is the flow rate in each fracture and e is the growth rate exponent. Each array was generated from a statistically equivalent initial aperture distribution. The figure shows that higher aperture growth rate exponents promote the development of enlarged localised channels and lower growth rate exponents lead to the development of a more generalised enlargement of the fracture network.



The nature of many fracture fills is likely to be highly sensitive to soil formation processes, processes associated with the weathering of cover rocks, palaeoclimates and recent climates. Fracture fills are discussed further in section 4.1, under the heading climatic and regional impacts on fracture distributions and characteristics. Fracture fills may have an important role to play in the chemical or microbiological transformation of contaminants in the fractures.

3.4 Modified Matrix Porosity Adjacent to Fractures

Although it has not been documented in the peer-reviewed literature, field observations and limited SEM studies have shown that matrix porosity adjacent to preferentially enlarged fractures in the Chalk may be significantly modified due to flow through parts of the fracture network. Field observations of weathering profiles across fractures suggest that cementation may occur behind fracture walls. For example fractures exposed in Chalk on a wave cut platform at the base of cliffs at St Margaret's Bay, Kent, UK exhibit characteristic profiles as a result of weathering. The matrix immediately adjacent to the fractures is more resistant to weathering and forms a small ridge away from the fracture up to about 5 centimetres wide. It is inferred that the ridges are more resistant due to a reduction in matrix porosity by cementation adjacent to the fracture. Other field observations suggest that the zones of inferred cementation may be highly complex and locally strong asymmetries in the weathering profile may develop on either side of the fractures.

The field observations are supported by limited scanning electron microscope (SEM) studies. For example, Bloomfield (1994) used low magnification SEM images (backscattered mode) of thin sections through chalk matrix adjacent to a fracture surface to investigate the development of enhanced porosity behind fracture walls. The fracture surface studied showed evidence of recent groundwater flow, i.e. there were clay drapes and the surface was stained orange. Immediately behind the fracture surface there was an increase in total matrix porosity and locally, an increase in pore throat size (up to about 100 microns). Away from the fracture there was a decrease in total porosity due to cementation of the matrix. The observed porosity variation was on a millimetre scale, an order of magnitude less than the features described from the field at St Margaret's Bay, Kent, UK.

Modification of matrix porosity adjacent to fractures may have important implications for the movement of contaminants in the Chalk. Aqueous diffusive exchange between mobile fracture water and relatively static matrix pore waters is an important control on the migration of solutes in the aquifer (Foster 1993). The degree of exchange between fracture water and matrix water depends on the density of fractures, the velocity of flow in the fractures, the aqueous diffusion coefficients of the species involved and the extent to which the fracture walls impede diffusion. Apparent diffusion co-efficients have been obtained for the matrix of the Chalk and are in the range 0.28 to 3.51×10^{-10} $m^1 s^{-1}$ (Hill 1984). Sandstones and granites with much lower porosities than Chalk (e.g. 2 to 9%) have apparent and effective diffusion coefficients one to three orders of magnitude less than those of the Chalk matrix (Gooddy et al. 1995). Consequently, if the porosity of the Chalk is reduced to a few percent in the vicinity of hydraulically active fractures there is the potential for a significant reduction in the diffusive exchange of solutes between water flowing in the fracture and the static pore water.

3.5 Summary

In summary, the Chalk departs significantly from the idealised model of a dual-porosity aquifer as shown in **Figure 1**. Five components of porosity have been identified in the Chalk. These are,

- Matrix porosity
- Fracture porosity
- Enlarged fracture porosity
- Fracture fill porosity, and
- Modified matrix porosity associated with transmissive fractures

Due to their relatively large apertures, it is the preferentially enlarged component of the fracture porosity that provides the principal path for rapid flow of water and transport of pollutants. The detailed structure of this component of the fracture network (including fracture fills and the modified matrix porosity near the flowing features) affects the extent to which contaminants will be retarded or attenuated. Chemical and microbiological processes may also act to retard or degrade contaminants along these pathways. The unenlarged fracture porosity and smaller fractures are thought to contribute to the specific yield and drainage. Consequently, an understanding of this component of the fracture porosity is important for resource modelling.

Pore waters are held essentially immobile in the matrix and do not contribute to flow. However, diffusion of contaminants into the chalk matrix is an important process that will act to prolong the persistence of non-degradable contaminants. Modification of matrix porosity associated with transmissive fractures may effect the potential for diffusive exchange between fracture and pore waters.

Calculations or models of hydraulic conductivity based on simplified fracture architecture and fracture aperture distributions (see **Figures 1** and **2**) have been used as part of local or regional groundwater resource studies. However, this ‘effective medium’ approach, that predicts average conductivity or storage parameters, will be of little use in contaminant transport studies where breakthrough times and concentrations are highly sensitive to the heterogeneous nature of flow through the connected fracture network. Consequently, a good understanding of fracture distributions, and specifically the processes leading to the development of the preferentially enlarged sub-networks, is vital to the development of predictive models of contaminant transport, and effective monitoring and the development of remediation strategies at contaminated sites on the Chalk.

4. FRACTURE CHARACTERISATION IN THE CHALK

In this section, more detailed characteristic features of fracture distributions and fracture network architecture in aquifers such as the Chalk are considered. Particular emphasis is given to identifying and characterising fracture connectivity and aperture distributions. First a few terms related to fracturing need defining.

A variety of terms have been used in the hydrogeological and engineering geology literature to describe planar partings in aquifers, and particularly in the Chalk the terms 'fissure' and fracture have often been used interchangeably. A range of fracture types may be identified in the Chalk, each with characteristic distributions of, for example, size, orientation and spacing, and it is useful to be able to distinguish between these different types of fracture. Consequently, a consistent nomenclature has been adopted in this report and throughout the FRACFLOW project. The following section presents the preferred definitions which are summarised in Box 5.

4.1 Some Definitions of Fracturing used throughout this Report

Discontinuity is a general term for a planar sedimentological or structural feature and *fractures* are discontinuities that have accommodated strain by brittle failure. A group of parallel or sub-parallel fractures form a *fracture set* and all fractures in the rock-mass 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.

Individual 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 4**.

It is helpful to distinguish three specific types of fracture in carbonate aquifers, such as the Chalk, i.e. '*bedding plane parallel fractures' or bedding 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).

Box 5. Summary of main fracture definitions

Discontinuity	General term for a planar fabric feature, either sedimentological or structural
Fracture	Discontinuities that have accommodated strain by brittle failure
Bedding fracture	Fractures located at discrete sedimentological boundaries or parallel to these boundaries
Joint	Fractures with no shear displacement at the scale of observation (Figure 3)
Fault	Fractures with shear displacement at the scale of observation (Figure 3)
Fracture set	A group of sub-parallel fractures
Fracture network	All fractures in the rock-mass

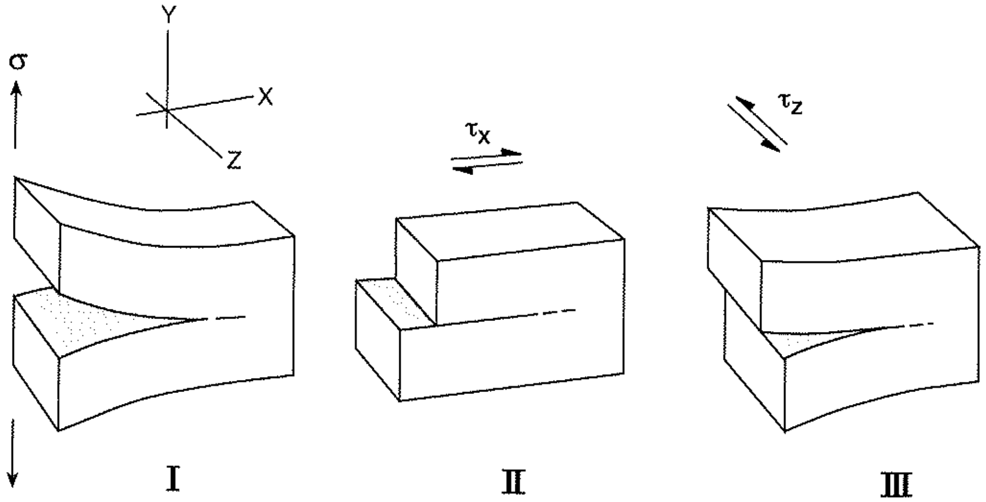


Figure 4. **Three basic modes of displacement at a crack tip. Mode I displacement perpendicular to the crack plane. Mode II displacement parallel to the crack plane and perpendicular to the crack edge and Mode III, displacement parallel to the crack plane and crack edge (after Paterson 1978).**

Bedding fractures are structures that are located at discrete lithological boundaries (Bloomfield 1996) or parallel to bedding planes. Lithological variations across these boundaries may be relatively pronounced, as for example, at the contact between marls and relatively pure chalk, or they may be subtle, consisting only of changes in the degree or nature of cementation of the matrix. In the Chalk, bedding fractures may be developed in association with marl seams, flint bands, hardgrounds or can be localised by any lithologically controlled changes in the density of the chalk. Bedding fractures may be laterally persistent when they are developed in association with laterally extensive transitions in lithology. Generally, bedding fractures are opening mode, or Mode I, fractures (**Figure 4a**), although if a marl or any other relatively ductile material is present in or near the bedding plane, then shear may have occurred across the surface and they may be Mode II or Mode III fractures.

Joints are also opening mode, or Mode I, fractures (Pollard and Aydin 1988). They characteristically form at high angles to bedding and/or false bedding surfaces and are usually bounded by bedding fractures. Where joints cut across more than one bed they are referred to as *multi-layer joints*. 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 they are referred to as *conjugate joints*. **Figure 5** (after Bevan and Hancock 1986) illustrates three different types of joints that they identified in a systematic survey of mesofracturing in the Chalk of southern England and northern France. The figure also indicates the inferred principal stress directions at the time of joint formation.

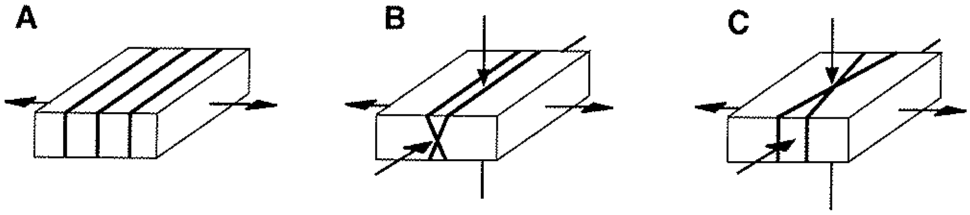
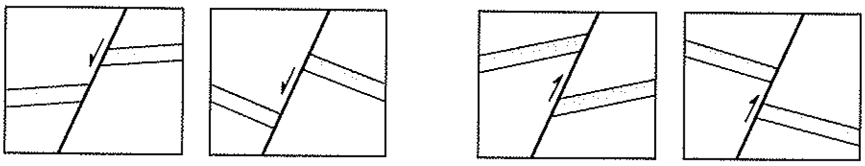


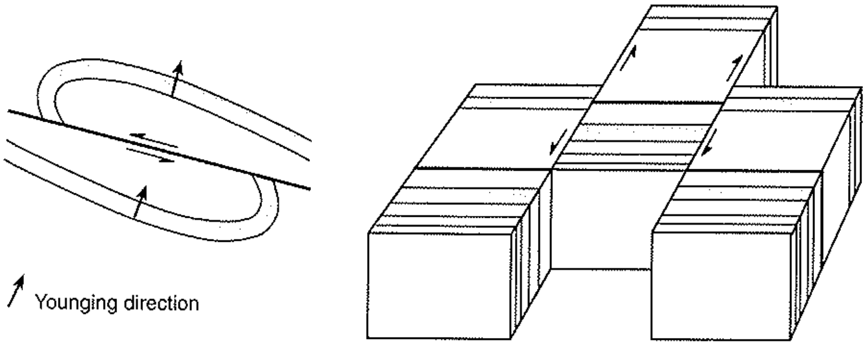
Figure 5. **Block diagrams of a. single set vertical extension joints, b. conjugate steeply inclined joints, and c. conjugate vertical joints. The arrows indicate the inferred directions of the principal stress axes (after Bevan and Hancock 1986).**

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. Each of these types of fault is illustrated schematically in **Figure 6**.



a) Normal faults

b) Reverse faults



c) Thrust fault

d) Wrench faults

Figure 6. **Illustration of fault geometries, a. normal faults, b. reverse faults, c. thrust faults (full arrows indicate the younging direction of the rock sequence, half arrows indicate the direction of movement on the fault plane, and d. wrench faults.**

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 *fault-bounded blocks* (**Figure 6**). 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 6**). Faults are rarely found in isolation and small faults are commonly clustered near larger faults. These concentrations of faults are called *fault zones*.

A characteristic set of structures may develop in fault zones in sandstones (Fowles and Burley 1994). These include a central slip surface and cataclastic slip bands. In carbonate aquifers, some of these structures are present but in the Chalk they are generally less pronounced, since deformation is more diffuse due to the relatively weak nature of this lithology. Cataclastic slip bands are not present in the Chalk. However, fault zones in the Chalk may exhibit slip surfaces containing striae of recrystallised calcite, known as *slickensides*. These indicate the most recent slip direction on the fault. Where the Chalk consists of a variety of lithologies, *i.e.* marls, hardgrounds and relatively pure chalk, 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. This material is referred to as *fault gouge* or *fault breccia*. Fault gouge is relatively fine-grained and fault breccia is relatively coarse.

4.2 Characteristic Features of Fracture Distributions in the Chalk

The purpose of this section is two-fold. Firstly, to describe the principal characteristics of fractures in the Chalk aquifer which are thought to be of most significance for the hydraulic behaviour of the aquifer, e.g. fracture connectivity and the possible geometries of preferentially enlarged fracture sub-networks. Secondly, regional trends in fracture characteristics in the Chalk of NW Europe and Israel will be briefly reviewed.

Table 1. **Summary of expected fracture distributions and characteristics for each of the principal fracture types in the Chalk.**

Fracture type	Parameter	Characteristics
Bedding fractures	Extent	Scale dependent, cm to 100s metres – controlled by lateral extent of sedimentary facies and/or bounding faults
	Spacing	Scale dependent, mm to 10s metres – controlled by lithostratigraphy, more frequent near ground surface
	Aperture	Scale dependent (?) mm to cm – largest apertures associated with preferential enlargement due to groundwater flow
Joints	Extent	Scale dependent, mm to cm – function of bedding plane spacing, often restricted to single beds
	Spacing	Scale dependent, cm – function of bedding plane spacing, more frequent near ground surface
	Aperture	Sub mm to mm – significantly less than maximum apertures associated with bedding fractures and faults
Faults	Extent	Scale invariant – power law distribution?
	Spacing	Scale invariant – power law distribution?
	Aperture	Effective aperture obtainable by hydraulic testing? Effective aperture may scale with fault size and displacement?

Fractures are a ubiquitous feature of the Chalk and are present over a very wide range of scales, from micro-fractures with lengths and apertures of a few tens of microns, to faults with lengths of hundreds of metres. Characteristic features of the three principal fracture types, bedding fractures, joints and faults can be considered separately. **Table 1** summarises the range of expected fracture distributions and characteristics for each of the principal fracture types in the Chalk.

Bedding fractures

Typically, bedding fracture spacing in the Chalk may vary from a few millimetres, in finely bedded marly intervals, up to tens of metres in massively bedded successions. The lateral extent, of bedding fractures in the Chalk may vary from a few tens of centimetres to hundreds of metres. There is significant uncertainty regarding the shape of bedding fractures. In plan view, bedding fractures may be circular or ellipsoidal in shape, but if bedding fractures abut against high angle fractures, such as faults, then they may be polygonal in shape.

The formation of bedding fractures may be associated with the removal of overburden and stress relief processes. Consequently, bedding fractures may be expected to be more numerous, more laterally extensive and have larger apertures at relatively shallow depths. The spacing of bedding fractures will be scale dependent, *i.e.* will be a function of the frequency of bedding surfaces in the chalk sequence, however, bedding fractures may not be present at all bedding surfaces. A second mechanism for the formation of bedding fractures is shear displacement along relatively weak horizons such as marls or within units of less well cemented chalk.

A characteristic feature of bedding fractures in the Chalk is their highly variable aperture (Bloomfield 1996). This may range from tens of microns to a few centimetres, with most apertures in the sub-millimetre to millimetre range. Highly irregular aperture distributions are likely to be a characteristic of individual bedding fractures, particularly where

- there has been displacement across the fracture, and/or
- the bedding fracture has been preferentially enlarged by abrasion, and/or plucking and/or dissolution.

There have been no systematic studies of fracture aperture distributions in the Chalk, however, (Bloomfield 1996) measured the aperture distribution in a single preferentially enlarged bedding fracture from the Chalk of southern England (see **Figure 7**). The apertures ranged from less than 0.5 mm to 23.5 mm, and approximated to a negative exponential distribution below 7 mm, and to a lognormal distribution above 7 mm. It was inferred that solution processes had affected the larger apertures.

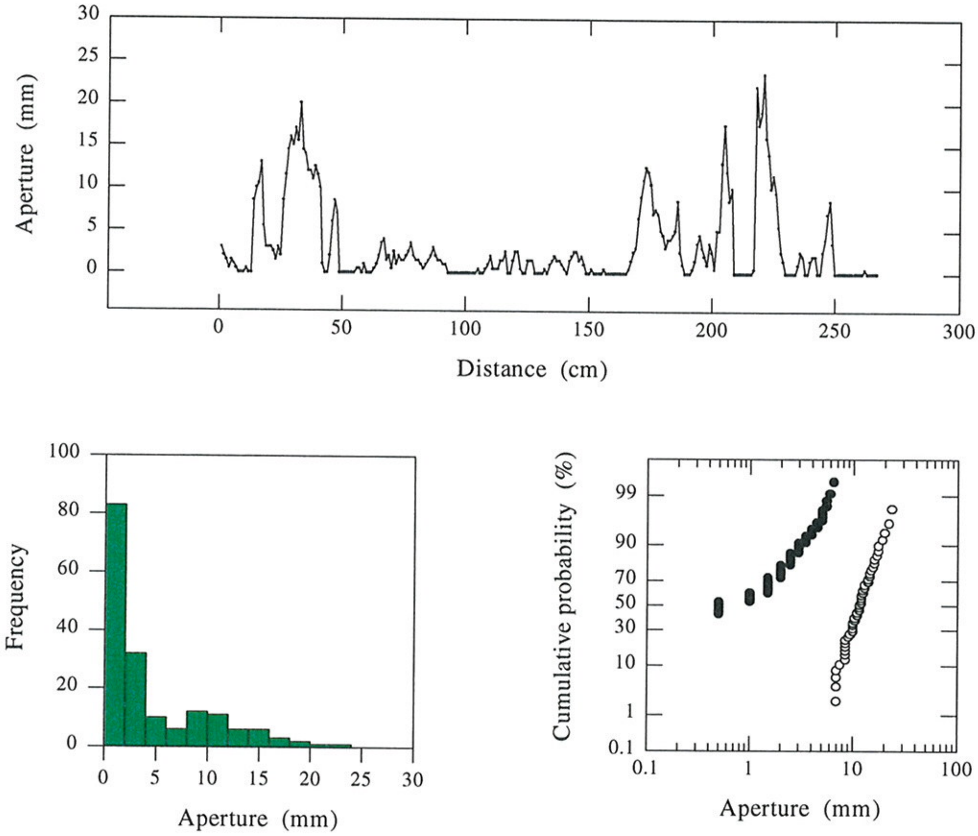


Figure 7. **Aperture distribution for a bedding fracture in the Chalk from Play Hatch Quarry, Berkshire, UK. The relatively large apertures are inferred to have been enlarged by groundwater flow processes (after Bloomfield 1997).**

Due to their lateral continuity, in areas where the Chalk has a relatively shallow dip, bedding fractures are likely to be the principal path for rapid sub-horizontal flow and contaminant transport. However, flow is expected to be strongly channelled within bedding fractures because of the variability in aperture and because of directional flow governed by the intersection of high angle joints with the bedding fractures. By comparing the bedding fracture aperture distribution shown in **Figure 7** with flow logs from a borehole near the studied exposure, (Bloomfield 1996) inferred that flow was essentially restricted to about 10 to 20% of the area of any given bedding fracture. The degree of flow channelling, particularly in bedding fractures is a major source of uncertainty in Chalk fracture characterisation and modelling. The concepts of channelling and the implications for flow and contaminant transport are described in more detail in the section on fracture network characteristics (see below).

Joints

Joints are the most commonly observed fractures at surface exposures. In flat-lying sedimentary sequences 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 direction (Cawsey 1977; Lorenz et al. 1991). 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.

Bahat (1990) has proposed a genetic classification of joints for the Chalk. Joints can be recognised on the basis of their geometry and surface characteristics as having formed during burial, subsequent uplift and in response to tectonic events. Each type of joint may have specific characteristics, for example, burial joints, thought to be associated with sediment diagenesis, generally exhibit relatively regular spacing and are restricted to single beds. In contrast uplift joints may be more irregularly spaced and crosscut more than one bed.

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. 1994). Generally there is an increase in jointing intensity towards the land surface due to stress relief and weathering processes.

In the Chalk joint spacing typically varies from centimetres in finely bedded sequences to a few metres in the most massively bedded Chalks and joint size may vary from a few centimetres to a few metres. For a given lithology and tectonic setting joint spacing and size generally decrease towards the ground surface. Joint apertures are expected to be much less variable than bedding fracture apertures and are typically in the tens of microns to millimetre range. Below the weathered zone in well-bedded sequences, joints are commonly restricted to single beds and terminate against bedding planes or bedding fractures and their size distribution is largely controlled by the distribution of bed thickness. These joints are inferred to have developed during burial Bahat (1990). However, in more massive sequences, where the mechanical characteristics of individual beds are relatively homogeneous, multi-layer joints may form in response to uplift.

Ladeira and Price (1981), Huang and Angelier (1989), Narr and Suppe (1991), and Mandal et al. (1994) have demonstrated that in sedimentary sequences the mean spacing of joints from a single joint set within a single bed is proportional to the thickness of the bed. 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 (a second orthogonal set of joints) are present, ladder- or grid-like, orthogonal joint systems can develop. Similar relationships may be present in bedded Chalk sequences.

For example, **Figure 8** is a plot of mean joint spacing against bed thickness for 26 different beds in the area of Flamborough Head, UK. This shows that there is a strong positive correlation between joint spacing and bed thickness. However other than the data summarised in **Figure 8**, there have been no systematic studies of the relationship between bed thickness and joint spacing in the Chalk

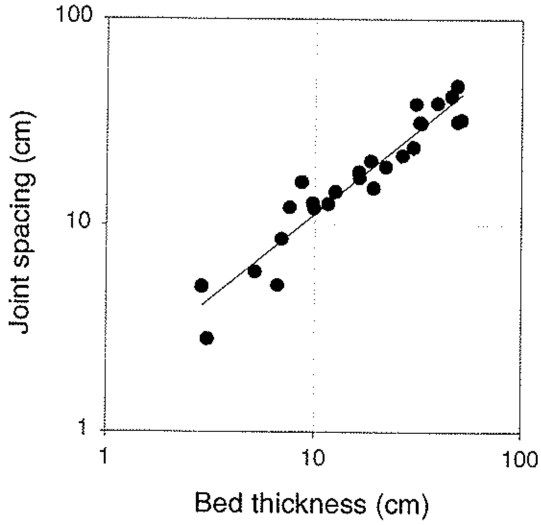


Figure 8. **Log-log plot of joint spacing versus sedimentary bed thickness for 26 beds from the Chalk of Flamborough Head, UK.**

There have been a number of site specific studies of jointing in various chalks in north-west Europe and Israel. Priest et al. (1976) measured negative exponential joint spacing distributions in the Lower Chalk at Chinnor, Oxfordshire, with a mean of approximately 0.05 m in the near surface weathered zone and a mean of approximately 0.1 m at depths exceeding 10 m. Bevan and Hancock (1986) described joint spacings in the range 0.1 m to >1 m from the Chalk of Kent, Sussex and Dorset, and Patsoules and Cripps (1990) noted joint spacings in the range 0.15 m to 0.33 m from the Chalk of Yorkshire. Younger and Elliot (1995) measured joint spacings in the Chalk parallel and normal to bedding and obtained mean values in the ranges 0.07 m to 1 m and 0.1 to 2 m respectively. Bloomfield (1996) measured lognormal joint spacing and length distributions for two joint sets at Play Hatch Quarry, Berkshire. He measured mean joint set lengths of 0.15 and 0.3 m, and mean joint spacings of 0.1 and 0.12 m. Commonly, trace lengths for joints at a high angle to bedding in the Chalk are reported in the range 0.1 to 3 m (Bevan and Hancock 1986).

Patsoules and Cripps (1990) have reported joint apertures in the Chalk in the range 0.1 to 0.6 mm. Based on a model developed by Snow (1968) that relates hydraulic conductivity to fracture spacing and aperture, Foster and Milton (1974) and Reeves (1979) inferred fracture apertures in the range 0.5 mm to 4.0 mm. From geochemical modelling of radon activities Younger and Elliot (1995) have inferred fracture apertures in the range 0.45 to 0.9 mm for the Chalk. Joints and multi-layer joints in Eocene chalk near Beer Sheva, Israel have been extensively studied by Bahat and co-workers (e.g. Bahat 1986; Bahat 1987; Bahat 1987; Bahat 1988; Bahat and Grossmann 1988; Bahat 1990; Bahat 1997). A characteristic style of jointing in the region is bed restricted en echelon burial joints. These vary in size from a few centimetres to about 65 cm (Bahat 1986) and have two dominant orientations, trending about 330 and 060 degrees (Bahat 1987). Joint lengths have been recorded up to about 3 m but appear to be lognormally distributed. Joint spacing ranges from 2 to about 50 cm (Bahat 1987) with a broad non-continuous distribution. Semi-quantitative observations of joint apertures suggested a maximum aperture of about 0.5 mm with apertures typically less than 0.1 mm.

Faults

Faults and fault zones are generally poorly exposed in onshore chalks. Where present, faults rarely form simple single breaks, but consist of sets of en-echelon fractures linked by areas of more distributed deformation, **Figure 9** (after Childs et al. 1996). Faults are generally clustered into zones of relatively diffuse displacement. Often larger faults, which may be controlled by structures in the underlying basement rocks, may only be recognised by the presence of large or well-developed valleys. Faults that can be seen at Chalk exposures are generally high angle extensional or normal faults associated with uplift of the sequence. Zones of dilation (increased bulk porosity), including increased fracture intensity and the opening up of bedding fractures, may develop between pairs of high angle extensional faults. Low angle extensional faults may also be seen in association with bedding fractures located on particularly weak horizons.

Unlike bedding fractures and joints, where size and spacing are scale dependent, fault spacing, size and displacement have generally been shown to be scale invariant (e.g. Gillespie et al. (1993) present a comparative study of joint and fault distributions). One of the consequences of fault scale invariance 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. Because of the inferred scale invariance of fault size in the Chalk, not all faults will be restricted to single beds. Larger faults are expected to cross-cut a number of beds and so may act as potential pathways for vertical flow or transport or as potential baffles or barriers to flow and transport in the saturated zone of the aquifer depending on the hydraulic characteristics of the fault or fault zone.

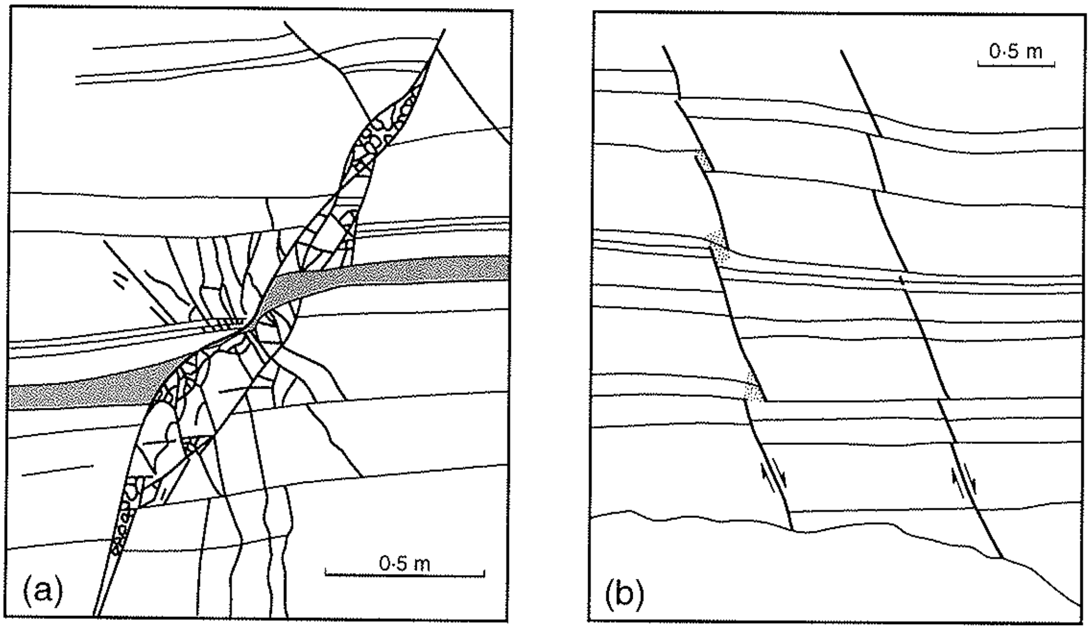


Figure 9. Two examples of the non-planar nature of faulting in the Chalk (after Childs et al. 1996).

There have been few systematic studies of faulting in onshore chalks, primarily due to the limited exposure of the chalk. Peacock and Sanderson (1994) identified 1340 minor faults over a 6 km long section of the Yorkshire coastline, in north east England. Displacements ranged from 5 mm to 6 m and spacings were in the approximate range 1 to 70 m. The majority of the faults were discrete surfaces; however, some faults were grouped to form complex zones of fracturing. Similar fault zones have been described from other localities in Europe by Koestler and Ehrmann (1987, 1991), Koestler and Reksten (1994) and Childs et al. (1996). Peacock and Sanderson (1994) noted a wide variation in the dip directions of the small faults, with individual faults often showing sinuosity and strike variations in excess of ten degrees. They recorded an average dip of 64 degrees. These observations are consistent with those of (Koestler and Ehrman (1991) who studied fracturing in Chalk overlying a salt diapir at Laegerdorf, northern Germany. Fault zone bounded blocks of rhombohedral shape were identified with block widths of 100 to 150 metres. Within these fault bounded blocks deformation was characterised by an interconnected network of fractures (joints and smaller faults). **Figure 10**, a field sketch of faulting seen at Laegerdorf Quarry (after Koestler and Ehrman 1991) shows characteristic features of faulting in the Chalk. These include clustering of small faults near larger faults, the non-planar nature of faults and antithetic faulting.

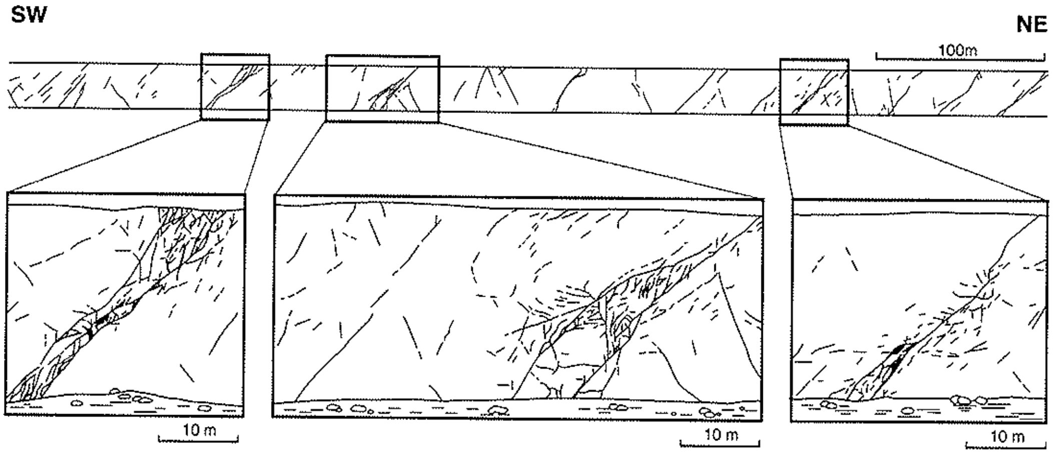


Figure 10. **Field sketch of faulting at Laegerdorf Quarry (after (Koestler and Ehrman 1991).**

Given suitable exposure it is possible to obtain sufficient measurements of bedding fractures and joints to characterise their respective aperture distributions. However, faults differ from bedding fractures and joints in that even under ideal field conditions it would not be possible to ascribe an aperture distribution to a given fault plane or fault zone. This is because faults are rarely simple structures and in the Chalk they may consist of multiple sub-parallel, fault surfaces containing gouge or fault breccias.

Studies of well-bedded Chalk in Yorkshire (Childs et al. 1996) have shown that the offsets between individual fault surfaces in normal fault zone often occur at mechanically weak horizons. For example, they may occur at the intersection of faults and weak bedding planes or at fault-fault intersections. They are often associated with localised zones of intense brecciation and damage to the matrix (**Figure 9**). These damage zones at fault offsets are areas of increased porosity, and may form tube- or pipe-like structures within the plane of the fault zone. 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. Fault rocks may have significantly different porosities and permeabilities with respect to the matrix, and there is the potential to develop hydraulic anisotropy particularly across larger fault zones. In sandstones, faults with larger displacements generally show greater thicknesses of fault rock (Knott 1994).

Fracture network characteristics

If an idealised fracture network is to transmit groundwater or carry contaminants between two points (e.g. a pollution source and a receptor, such as a public supply borehole or spring), the points must be joined by a continuous path of connected fractures (Berkowitz and Balberg 1993). Consequently, the two most important factors in fracture transport are fracture connectivity and the aperture distribution along the connected path. Unfortunately these parameters cannot be measured directly in the field and it is usually necessary to develop conceptual and numerical models based on limited field data. The following section briefly reviews some of the theoretical approaches to the characterisation of fracture connectivity and aperture distribution, and describes some of the features of chalk fracture networks that are thought to be most hydrogeologically significant for the rapid transport of contaminants.

Quantitative definitions of fracture connectivity usually relate some measure of fracture density to the number of intersections in 2- or 3-D. For example, Guerin and Billaux (1994) defined a connectivity index, I_c, as the mean number of intersections per fracture, weighted by the fracture size (diameter). There is a large body of literature on fracture system models (see Dershowitz and Einstein (1988) for a review) that are used to represent natural fracture distributions. The nature of fracture connectivity in these models will vary according to the connectivity index used.

Dershowitz and Einstein (1988) describe a range of modelling approaches to characterise fracture connectivity; these include both deterministic and stochastic tessellations. The orthogonal array in **Figure 1** is an example of a deterministic tesselation. Structures generated by random Poisson process, such as Voronoi tessellations are an example of stochastic models.

Fracture arrays like these can be generated relatively easily using proprietary modelling packages, and much of the field work on fracture characterisation that has been carried out to date has been aimed at providing data on fracture characteristics to condition both deterministic and stochastic types of fracture system models.

In these models, connectivity is sensitive to a range of individual fracture characteristics (location, size, shape, orientation, and planarity) of fracture set characteristics (spacing, spatial correlation, and co-planarity) and of multiple fracture set characteristics such as fracture intensity.

In addition to the geometrical constraints on fracture connectivity, the concept of hydraulic connection may also be considered to be time dependent. For example, the majority of the pore space in the Chalk aquifer (the matrix porosity) is connected. But for the purposes of contaminant transport, two points a few hundred metres apart (e.g. contaminant source and breakthrough point) may only be considered to be hydraulically ‘connected‘ if they are part of a connected fracture sub-network that controls contaminant breakthrough at an arbitrary time. The time may, for example, be the travel time defining a source protection zone at a public supply borehole.

Percolation theory also provides a definition of connectivity, the critical percolation threshold, p_c (Berkowitz and Balberg 1993). When fractures are added randomly to a regular grid they begin to form clusters. Below the percolation threshold a finite set of fracture clusters may be interconnected, but the connections between clusters will not be complete. At the percolation threshold (equivalent to a critical fracture density) an infinite cluster forms, **Figure 11**. For finite arrays this means that an array spanning or percolating cluster forms. The value of the percolation threshold depends on the geometry of the array (e.g. 2- or 3-D and co-ordination number) and requires random population of the array.

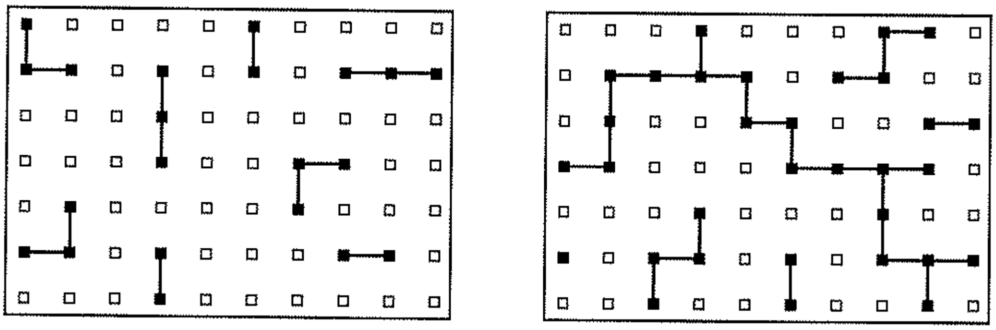


Figure 11. **Illustration of the concept of critical percolation threshold. The left-hand figure shows small finite clusters that are internally connected but do not percolate. The right-hand figure shows the development of a percolating (array-spanning) cluster at the percolation threshold.**

In shallow fractured sedimentary aquifers, such as the Chalk, where the fractures are prone to enlargement due to groundwater flow, flow may be channelled through sub-networks that have undergone preferential enlargement (see section 2.2 and **Boxes 3** and **4**). A number of potentially hydrogeologically significant features of the fracture network can be identified either on the basis of their high degree of connectivity and/or on the basis of their relatively large actual or effective hydraulic aperture. Given an understanding of the geological controls on their distribution, these features or structural elements can be combined to provide a conceptual model of the Chalk fracture network.

Features of the fracture network in the Chalk that are thought to be of significance for flow and rapid transport of contaminants include,

Enlarged bedding fractures.
These are often, but not necessarily, associated with sedimentologically controlled features such as prominent flint bands, marls or hardgrounds, or are associated with surfaces where there has been some shear displacement (again often associated with marls).

Faults and fault zones.
Orange staining and infilled material in faults and fault zones near the ground surface indicate that they may have acted as potential pathways for subvertical movement. Their ability to act as hydraulic barriers is unclear. Dilational zones between en-echelon faults, see **Figure 9**, may form localised zones of enhanced conductivity. Dilational zones and zones of increased fracturing may be found between pairs of extensional faults or fault zones. However, some faults may act as barriers to flow.

Multi-layer joints
Multi-layer joints may develop when the mechanical behaviour of the Chalk beds is dominated by a set of beds rather than individual beds. Once formed they may also act as a pathway for sub-vertical groundwater movement and transport.

Intersection between two prominent fracture sets
Intersections between bedding fractures and high angle fracture sets will form linear features in the plane of bedding. Intersections are also possible between two high angle fracture sets. Where faults intersect weaker bedding planes a zone of damage may preferentially develop and flow within a bedding plane may be localised within this feature. Fracture intersection directions will be most hydrogeologically significant where they are parallel or sub-parallel to the local or regional hydraulic gradient.

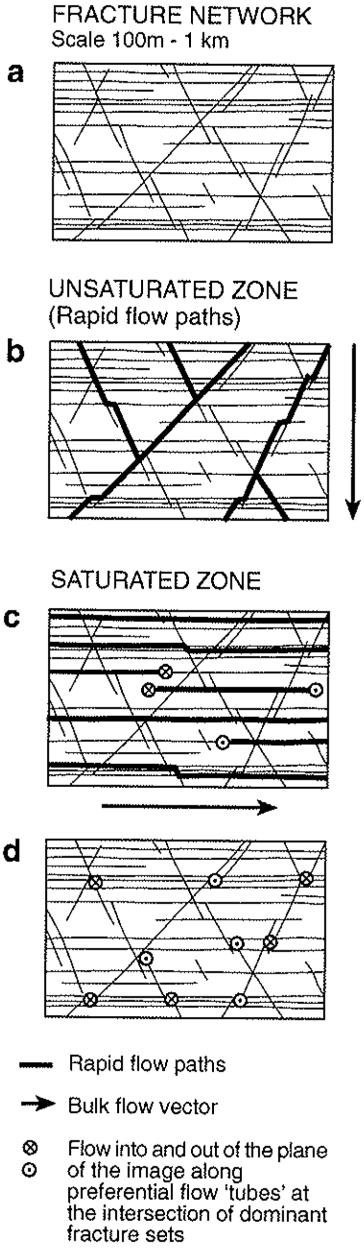


Figure 12. **A conceptual model illustrating fracture control on rapid groundwater flow and transport in the unsaturated and saturated zones of the Chalk aquifer. Figure 12a. shows the fracture network consisting of faults and bedding fractures. Figure 12b. indicates the geometry of preferential rapid flow paths in the unsaturated zone, and Figures 12c. and 12d. the geometry of rapid flow paths in the saturated zone. The heavy lines indicate parts of the fracture network that are likely to undergo rapid flow for a given bulk flow vector.**

Figure 12 shows a simple conceptual model of how chalk fracture architecture may affect the rapid ground water flow and transport and how different components of the network affect rapid flow and transport in the saturated and unsaturated zones. The model envisages the aquifer as consisting of blocks of Chalk defined by relatively continuous sub-horizontal bedding fractures and relatively large sub-vertical fractures (either faults, fault zones, or multi-layer joints). Rapid flow may be localised at intersections between the fracture sets. Rapid flow will also be concentrated along different components of the fracture network, in response to the orientation of the bulk groundwater flow vector.

4.3 Regional Trends in Fracturing in the Chalk

The following section briefly describes some of the regional trends in fracturing in the Chalk of north-west Europe and in the Eocene Chalk of central and southern Israel.

Regional trends in Chalk fracturing in north-west Europe

Downing et al. (1993) provide a concise overview of the depositional history, distribution, thickness variations, and lithostratigraphy of Upper Cretaceous chalks in north-west Europe. They also provide a concise description of the influence of tectonics on the structure of the Chalk in this region. Regional fracturing trends are principally related to the regional stress history. Alpine compression in north-west Europe, initiated in the Tertiary, has produced a maximum horizontal stress with a NW-SE alignment that tends to produce NW-SE and NE-SW trending fractures. Where well developed, this fracture system may effect the surface topography and drainage pattern. For example in north-west France lineaments in the Chalk control a rectilinear drainage pattern draining north-westward into the English Channel (Downing et al. 1993). In addition to the NW-SE and NE-SW oriented fractures, in southern England a series of E-W trending flexures can be recognised with associated N-S and E-W fracturing.

Bevan and Hancock (1986) described five fracture styles in the Chalk of north-west Europe; (i) vertical extension joints, (ii). conjugate steeply inclined hybrid joints, (iii). conjugate vertical joints, (iv). conjugate steeply inclined shear joints and (v). conjugate normal meso-faults. The most common fracture types were vertical extension joints and conjugate steeply inclined joints. Bevan and Hancock (1986) demonstrated that the dominant regional fracture fabric in the Chalk of NW Europe trends NW-SE (with a minor cross-cutting NE-trend) oblique to the dominant fold trend and that this orientation applies to both joints (extensional fractures) and faults (shear fractures), **Figure 13**. The work of Bevan and Hancock (1986) was primarily based on surface exposures and shallow quarries. There is only limited evidence for the presence of the regional fracture sets at depth in the Chalk, as sub-vertical joints are generally poorly sampled by boreholes. However, these regional fractures are probably developed throughout the full thickness of the Chalk, for example they have been recorded to the base of the Lower Chalk, at a depth of approximately 270 m, in the Fair Cross borehole of southern England.

Detailed studies of fracturing intensity and style in the Chalk of the Paris Basin and southern England (Mortimore 1993; Mortimore and Pomerol 1997) have suggested that there may be components of both structural and stratigraphic control. For example, in the South Downs in southern England (Mortimore 1993) has described changes in jointing style across the Hollingbury Dome, a small anticlinal structure. In the crest of the anticline orthogonal jointing is found in the homogeneous white Seaford Chalk, but on the flanks of the structure steeply inclined, conjugate jointing is present in Newhaven Chalk. The latter contains a number of marl seams. The difference in fracture style was inferred to be related to both structural position and the mechanical competence of the beds.

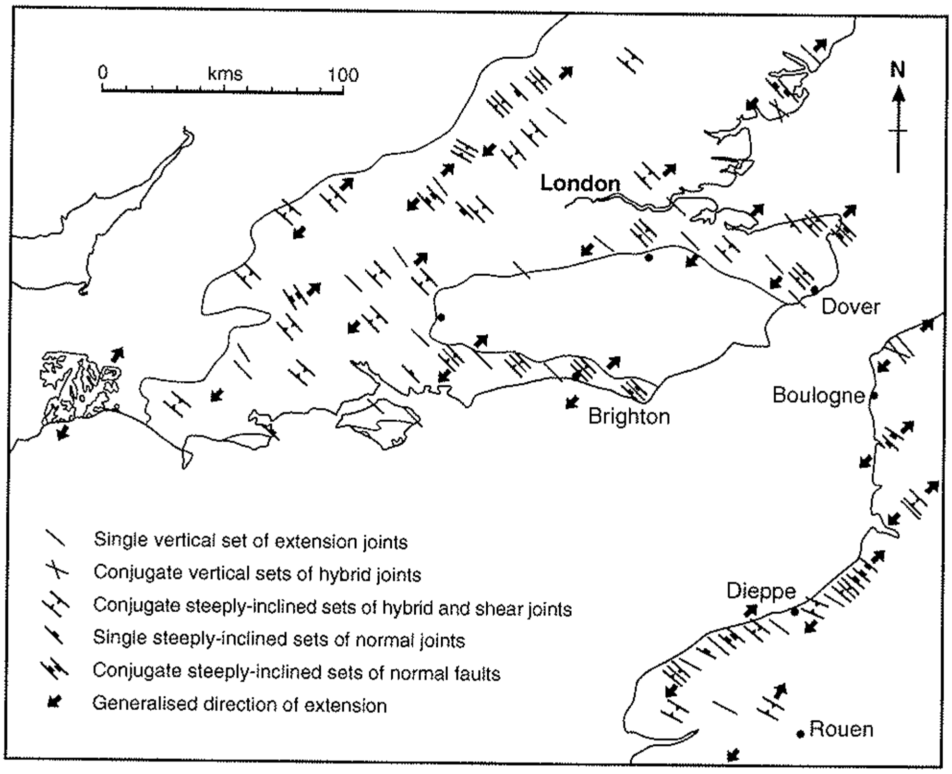


Figure 13. **Fracture orientations and major lineament directions in the Chalk of NW Europe (after Bevan and Hancock (1986).**

Regional trends in Chalk fracturing in Israel

The Eocene chalks of central and southern Israel are preserved in a series of faulted open synclines. The axes of these synclines swing from a roughly E-W or NE-SW orientation away from the Dead Sea Rift towards a N-S trend nearer the Rift. Eyal and Reches (1983) noted a change in deformation characteristics from the late Cretaceous to Neogene. This was characterised by the early development of long wavelength folds and monoclines in the late Cretaceous and normal and strike slip faulting during the Neogene to Recent. They associate this change in structural style with a change in the regional stress field. The earlier stress field, with a dominant maximum horizontal compression trending W to WNW, in the late Cretaceous to Neogene, was associated with the folding to the west of the Dead Sea. The later stress field, in the Neogene to Recent, had a dominant horizontal extensional stress trending E to ENE and this primarily affected the rift, and near rift, structures.

Due to relative complexity of structures near the Dead Sea Rift and the changing regional stress field, it is difficult to identify regional fracture orientations in the Eocene Chalks. However, histograms of joint orientations from around syncline centred on Beer Sheva, in the Negev of southern Israel (Bahat and Grossmann 1988) suggest that regional extensional joints are predominantly oriented NE-SW, **Figure 14**.

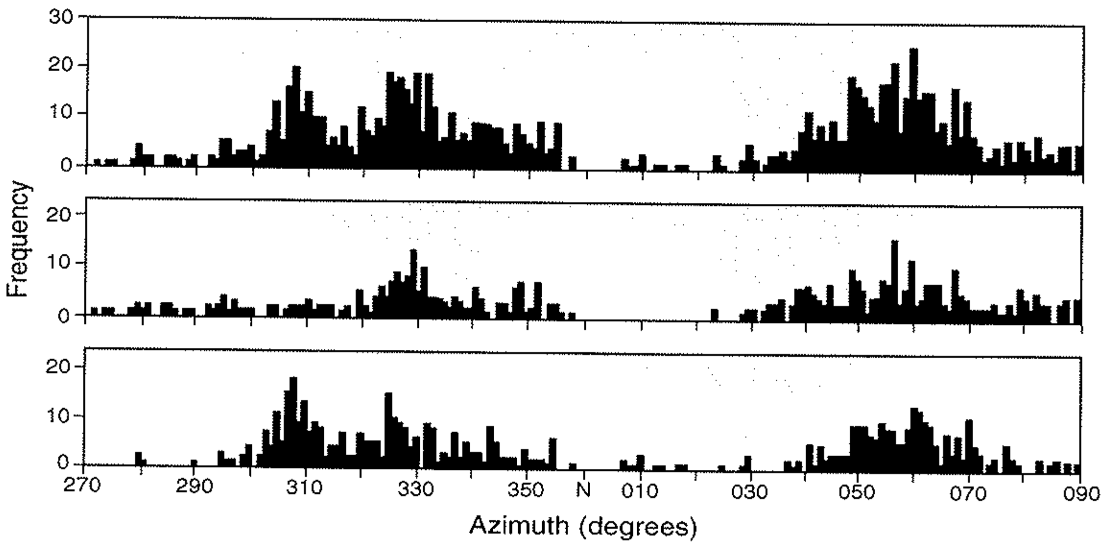


Figure 14. Fracture azimuth data for Eocene Chalks from the Ber Sheva region of southern Israel (after Bahat and Grossmann 1988).

5. PHYSICAL PROPERTIES OF FRACTURE SURFACES, FRACTURE FILLS AND MATRIX ADJACENT TO FRACTURES

In this section we briefly consider the physical properties of fracture surfaces, fracture fills and matrix adjacent to fractures, the influence of climate on these features, and their potential significance for contaminant movement in the Chalk aquifer.

There have been no systematic studies of the physical properties of fracture surfaces, of the matrix adjacent to fractures, or of the nature of fracture fills in the Chalk, although they would provide both insights into the hydrogeological development of the aquifer and information on contemporary transport processes.

Surface properties of fractures and the extent of secondary mineralisation or fills may be important controls on the diffusional exchange of dissolved solutes between fractures and matrix water. Iron and manganese hydroxides, clays and organic materials on fracture surfaces may act to coprecipitate and/or scavenge trace metals and may have important consequences for element mobility in shallow aquifers (Shand and Bloomfield 1995). Additionally, the transport of pesticides and pathogens may be strongly effected by sorbtion onto clays on fracture surfaces.

5.1 Climatic and Regional Impacts on Fractures and Fracture Fill Characteristics

The physical properties of fracture surfaces, fracture fills and matrix adjacent to fractures is expected to be dependent on the extent to which the fracture network has been subject to freshwater circulation, the nature of any cover deposits, and (particularly for shallow fractures) the nature of recent and contemporary weathering. It is therefore reasonable to expect systematic differences between fracture surfaces and fracture fills developed in the Cretaceous Chalk in the relatively humid conditions of north-west Europe and the relatively arid conditions of central and southern Israel where Eocene chalks outcrop.

For example, in north-west Europe, bedding fractures in the Chalk may contain infills or linings of chalk rubble, and/or sand and/or clay (Bloomfield 1996). The origin of these deposits is uncertain. Clay linings and chalk rubble may have been generated *in situ* in response to weathering of the fracture associated with groundwater flow, however, it is thought that sands and clays may have been washed in from overlying Palaeogene deposits (Younger 1993). These fills have not been studied systematically, but may modify the hydraulic conductivity of the bedding fracture significantly. Where karst development has occurred the features may be infilled with overburden deposits, e.g. van Rooijen (1993) has described solution features filled with Quaternary deposits from Belgium. Shand and Bloomfield (1995) have described the physical and mineralogical properties of selected fracture surfaces from a site on the Chalk in Hampshire, UK. Using material from the same site Bloomfield (1994) has described variations in matrix porosity behind fracture surfaces inferred to have been hydraulically active (see section 2 of this review).

In Israel, bedding fractures near the ground surface commonly contain gypsum and clays (Issar et al. 1988). The gypsum veins are associated with loess-soil cover and it is inferred that gypsum precipitation occurs through a process of leaching from the loess. Avigour and Bahat (1990) have described calcite crystals, soft fine-grained carbonate material and Fe- and Mn-oxides within fractures, including bedding fractures, in the Eocene chalks of the Negev. Based on geochemical evidence these fills were also inferred to be due to *in situ* weathering of the fractures, either due to local runoff or groundwater circulation.

In summary, little is known about this potentially important aspect of fracturing in the Chalk, and there is scope for a systematic survey of the nature and occurance of fracture surface properties, fracture fills and matrix modification adjacent to fractures. Systematic trends should be sought between different hydrogeological setting, i.e. arid versus humid, with cover and without cover, and within a given hydrogeological setting trends with depth. It is not clear how these features may vary between the unsaturated and saturated zones of the aquifer.

6. TECHNIQUES USED TO CHARACTERISE POROSITY IN THE CHALK

A wide range of methods are available for characterising matrix and fracture porosity in sedimentary rocks. These methods include direct measurement of fracture characteristics at outcrop or on core material, and indirect methods, such as interpretation of air photographs and borehole geophysical logs. Laboratory methods may also be used to characterise the detailed morphology and structure of fracture surfaces and the chalk matrix.

This section briefly describes the most important methods and techniques that have been used to characterise porosity in the Chalk. It highlights some of the strengths and/or weaknesses of each technique and assesses their applicability to the investigation of pore space geometry in the Chalk aquifer. **Table 2** summarises the techniques used to characterise fracture porosity and **Table 3** summarises techniques used to characterise matrix porosity.

Table 2. **Summary of fracture survey techniques, including geological surveys and geophysical logging.**

Geological Survey Techniques

Technique	*Advantages*	*Disadvantages*
1. Remote sensing 1a. Aerial photography 1b. Digital terrain maps	Rapid and cost effective assessment of catchment scale structures	Can only be used in areas where topography reflects underlying geological structure.
2. Field geological surveys 2a. Fracture mapping 2b. Scan-line survey 2c. Lithostratigraphic mapping	Valuable source of quantitative information on fracture size, orientation, and spacing at local scale. Only direct method of assessing geometry of fracture network and connectivity. Enables relationships between fracturing and lithology to be studied.	Requires skilled staff, can be labour intensive and may be relatively expensive. Needs good surface exposure. When used in isolation difficult to extrapolate to depth and does not provide information on groundwater flow
3. Core logging 3a. Direct core logging	Core logs provide quantitative information on fracture orientation and spacing, fracture surface mineralisation.	Obtaining core is expensive. In highly fractured chalks, particularly in the unsaturated zone core loss may be significant.

Geophysical Survey Techniques

Technique	*Advantages*	*Disadvantages*
1. Surface geophysics 1a. Shallow surveys 1b. Deep seismic surveys	1a. can be used to 1b. used to locate larger structures	1a. relatively expensive (1b. ver expensive). 1a. used in Denmark but untested in most of Europe
2. Borehole geophysics (direct) 2a. Borehole TV 2b. Formation microscanner 2c. Azimuthal laterlog 2d. Flow logs	Continuous digital logs of fracture occurrence in borehole (can be compared with core logs). Provide information on fracture spacing and aperture (2b. and 2c. only).	Expensive techniques, only provide information on fractures adjacent to the borehole, and most do not provide direct information of groundwater flow.
3. Borehole geophysics (indirect) 3a. Caliper logs 3b. Microresistivity logs 3c. Dip meter logs 3d. Sonic logs 3e, Gamma ray logs	Provide a range of continuous digital logs that can be correlated with direct geophysical logs and core logs to provide information on matrix and fracture porosity.	Do not provide direct information on matrix or fracture porosity. Significant confusion is possible in interpretation, for example natural and induced fractures. Some logs very sensitive to ambient borehole conditions.

Table 3. Summary of techniques used to characterise matrix porosity.

Laboratory Thin Section And SEM Techniques		
Technique	*Advantages*	*Disadvantage*
1. Porosimetry 1a. Liquid resaturation porosimetry 1b. Helium porosimetry	Matrix porosity can be measured to an accuracy of +/- 0.5%. Bulk and grain density may also be measured.	Only relatively small samples, c 25 mm in diameter, can be tested. Technique relatively expensive as part of a hydrogeological investigation.
2. Pore-size distribtuion 2a. Mercury porosimetry	Provides information on the pore-throat size distribution and bulk porosity.	Only relatively small samples, c 9 mm in diameter, can be tested. Technique expensive as part of a hydrogeological investigation.
3. SEM analysis	Provides qualitative information on matrix porosity and fracture characteristics at the microscale.	Only microscale observations are possible, consequently there may be difficulty extrapolating the results. Costly non-standard tests.

6.1 Regional and Field Geological Surveys

If surface topography is controlled by structures within the Chalk, at the regional and catchment scales structural lineaments may be identified using aerial photos and digital terrain maps. Where present, the orientation of these large-scale structures is usually controlled by structures in the underlying rocks (Mortimore 1993). If available, siesmic sections may provide information on underlying structures and associated zones of deformation in the overlying Chalk. Mortimore and Pomerol (1997) have used shallow seismic sections from the Anglo-Paris basin to identify structures within the Chalk related to intra-Upper Cretaceous tectonic phases.

At the sub-catchment scale systematic surveys of fracture characteristics at outcrops provides the most detailed information of fracture distributions and 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. Qualitative information can also be obtained on fracture connectivity.

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.

Fracture characteristics are obtained at outcrop using scan-line surveys (Priest and Hudson 1981; Priest 1993). Scan-line surveys are performed by placing a randomly oriented sample line over structures that are to be measured. Only structures that intercept the sample- or scan-line are recorded. It should be noted that true joint lengths cannot be measured at an outcrop. This is because the shape and position of a given joint relative to the exposure surface is not known, however joint trace lengths (chords through joint surfaces) can be measured by scan-line surveys on planar or near planar exposures. Bloomfield (1996) described the characterisation of hydrogeologically significant fractures in the Chalk using scan-line surveys.

Measurements obtained from scan-line surveys can be subject to significant biases (Priest and Hudson 1981; Priest 1993). Firstly, a scan-line will tend to preferentially sample larger joint traces. Secondly, the largest traces may extend beyond the visible exposure, 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.

Stereo-photographic pairs of images of outcrops can be digitised and analysed using appropriate software. The resulting data can be analysed using virtual scan-lines to provide information on fracture size, orientation and spacing (although fracture aperture data and observations on fracture mineralisation are not possible). This technique requires specialist equipment and has not been used to analyses fracturing in the chalk. However, it may be a useful research tool for investigating exposures where there is a problem of stability of the exposure, or where the face may be contaminated or where there are severe time constraints on access to the exposure.

Analysis of cored borehole material can provide detailed information concerning fracturing in the immediate vicinity of a borehole. Although as most boreholes are subvertical, fractured core logging generally provides only limited data on high angle fractures and normal faults may be poorly sampled.

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. Kulander et al. (1990) provide a detailed description of fractured core analysis.

6.2 Geophysical Survey Techniques

There are a variety of geophysical methods that can be used to characterise fractures in sedimentary rocks. Surface geophysics 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 chalk 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 aquifers are described in the following sections.

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. 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.

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. Additionally, if there is any drilling mud cake on the well wall then this may significantly impede the use of downhole cameras.

The borehole televiewer, or formation microscanner, 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 fluid level.

Generally, indirect methods, such as calliper 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. Many of these techniques also require the borehole to have relatively smooth walls that are not covered in drilling mud or debris. Ideally they should be used in cored boreholes. 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. The resulting *caliper logs* can be used to detect zones of borehole enlargement and by implication fracture zones and intervals of weak rock. 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. The tool does not indicate the direction of an enlargement, and although caliper logs may detect horizontal fractures, they may miss short vertical fractures, depending on the orientation of their arms relative to the fracture system.

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 compared with the resistivity of the matrix. However, this technique is very sensitive to borehole geometry and formation conditions (fluid properties) because of the shallow 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 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 fractures; and could have use within a suite of logs for locating the position of bedding fractures. Uranium may be deposited along fractures because it is very mobile, and gamma ray logs may recognise this

Fluid logs (i.e. 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.

6.3 Laboratory Techniques

Standard core analysis can be used to characterise matrix porosity profiles. For example, Bloomfield (1997) used matrix porosity profiles to study the diagenetic controls on groundwater circulation at the western end of the London Basin (see **Box 2** section 2.2). Samples are taken from whole core and can be correlated with specific lithologies. Either liquid resaturation or helium gas expansion methods may be used.

Pore-throat size distributions, similar to those illustrated in **Figure 2**, are obtained by mercury injection capillary pressure tests (Price et al. 1976). Pore-throat sizes in the chalk generally show limited variation. However, there have been no systematic surveys of pore-throat sizes in nodular and marly chalks, or in chalk hardgrounds, and there have been no systematic surveys of matrix porosity in weathered chalk. Pore-throat size tests could be used, in conjunction with SEM studies, to investigate modifications in the nature of matrix porosity adjacent to hydraulically active fractures. Bloomfield (1994) reported on a scoping study to investigate the variation in porosity adjacent to a hydraulically active fracture using an SEM and image analysis on polished thin sections of Chalk. There appears to be significant potential to develop this technique to characterise matrix porosity near fracture walls. Extrapolation of the results will require the analysed samples to be tied to features that are observable in the field, such as stained fracture surfaces or preferentially enlarged fracture sub-networks.

7. IMPLICATIONS FOR CONTAMINANT TRANSPORT, SITE MONITORING, AND REMEDIATION

Unfortunately, the task of characterising fracture distributions in the Chalk is not trivial because fracture characteristics may exhibit spatial variation over a wide range of scales and are know to vary significantly with depth below ground level. In addition, because the Chalk is relatively soft and easily weathered there are generally few surface exposures and opportunities for direct observation of fractures is limited. Indirect methods, such as borehole geophysics techniques, may have an important role to play in the characterisation of fractures in the Chalk aquifer.

One of the central aims of this study is to demonstrate how knowledge of fracture distributions can be acquired and used to develop the most appropriate contaminant monitoring and remediation strategies for the Chalk aquifer. Defensible monitoring and remediation strategies are usually based on validated models of the natural system. However, a wide variety of techniques are available to model fractured dual porosity aquifers, and selection of the most appropriate modelling approach is not simple (Barker 1991; Barker 1993).

Given plenty of data on fracture distributions, usually at a local (borehole or outcrop) scale, a deterministic approach may be justifiable. At the other extreme, when little or no data are available an equivalent continuum approach may be considered more sensible, particularly if the scale, for example catchment scale, is significantly greater than characteristic size and spacing of the connected fractures. However, stochastic models may be more appropriate when there are limited fracture data at site or sub-regional scales. In addition, when selecting a modelling approach it is also reasonable to assess the nature of the available data. For example, for a given modelling approach, what fracture parameters are available, to what tolerances, and at what density of observation?

It is important to recognise the links between the modelling approach used at a contaminated site and the fracture characterisation programme that is required. Selection of specific modelling approaches may significantly effect the nature of any site fracture characterisation programme, and the nature of available fracture data may influence the selection of a given approach to site modelling.

From the above discussion, it is clear that to develop useful models of flow and contaminant transport geologist needs to provide modellers with a coherent conceptual model of the structure of fracture porosity at the required scale. In addition, it may also be necessary to provide either real or synthetic fracture porosity data. This review has highlighted a number of areas of significant uncertainty related to fracture characterisation in the Chalk, and as a consequence the conceptual models and data that geologist can provide for modelling purposes have a number of limitations.

The areas of most significant uncertainty related to the characterisation of fracture porosity are outlined below. It is hoped that FRACFLOW will address many of these topics.

7.1 Areas of Most Significant Uncertainty Related to Fracture Characterisation in the Chalk

It is helpful for the purposes of this review to subdivide the uncertainties related to fracture characterisation into three types of problem. The first set of problems are associated with our uncertainty regarding both individual fractures and fracture network structure. The second area of uncertainty is related to the processes that have produced the fracture porosity that we see today. The final set of problems is related to the practicalities of obtaining accurate and representative data on fracture and matrix porosity.

Structures

Five important areas related to the structure of fractured Chalk aquifers have been identified where there is still significant uncertainty regarding the fracture porosity. They are as follows

- **Fracture connectivity and fracture porosity at the intersection of fracture sets.** There are limited field observations regarding the nature of porosity at the intersection of faults with bedding fractures and the intersection of high angle fracture sets. Additional field observations are required.

- **Geometry of preferentially enlarged fracture sub-networks.** Preliminary modelling work suggests that systematic patterns of fracture enlargement may be recognisable. More direct field evidence of this type of hydraulically significant fracture porosity is needed.

- **Aperture distributions along connected, preferentially enlarged fracture sub-networks.** There is very limited data on fracture aperture distributions. Given the sensitivity of flow to fracture aperture it is important that additional field data should be obtained.

- **The characteristics of modified matrix porosity adjacent to hydraulically significant fractures.** Scoping studies suggest that matrix porosity modifications adjacent to hydraulically active fractures may be significant. Systematic sampling and investigation are necessary to confirm this observation.

- **Fracture porosity in the shallow weathered zone of the aquifer.** The nature of fracture (and matrix) porosity in the shallow weathered zone of the Chalk aquifer is very poorly constrained. There is ample evidence that the structure of the shallow chalk is sensitive to Recent and contemporary climatic influences. Although a systematic survey of the impact of weathering on pore structure in the shallow Chalk is beyond the scope of FRACFLOW a comparative survey of selected sites in humid north-west Europe and arid Israel would provide useful new data sets.

Processes

A detailed understanding of processes related to fracture porosity might appear relatively academic. However, given the many difficulties associated with obtaining representative fracture data, an understanding of the processes related to fracture formation would enable the generation of more realistic synthetic data sets for use in flow and contaminant transport models. Three particular areas have been highlighted. They are as follows

- **Development of the preferentially enlarged fracture sub-networks.** Little is known about the processes of fracture enlargement that has been identified in the 'humid' chalks of north-west Europe, although concentration of groundwater flow is thought to be an important factor. Field study of the distribution and surface characteristics of these features may reveal the hydrogeological context in which they developed.

- **Cementation of matrix.** Detailed observation and chemical analysis would enable the timing, and mechanisms of matrix cementation adjacent to hydraulically active fractures to be investigated. An understanding of this process could provide information on which components of the fracture system are most prone to cementation.

- **Weathering and fracture formation near surface.** A scoping study of processes in the shallow chalk that modify fracture porosity would enhance field observations on structure. Studies on Eocene chalks from Israel have shown that movement of fines in fractures modifies their porosity distribution and that their structure may be considered meta-stable. Is it possible to make similar observations on the Chalk of north-west Europe where there is variable but locally thick cover?

Studies in each of these areas would benefit from modelling of the processes.

Techniques and approaches

A variety of techniques to characterise fracture and matrix porosity were described in Section 5. Individually they may only be of limited use, however, when used in combination, particularly with hydraulic tests, they may offer a far more powerful method of understanding porosity structure and hydraulic behaviour.

Boreholes in the Chalk are typically oriented vertically, usually sub-perpendicular to bedding, consequently, they represent a biased sample of the fracture system. Where high angle structures are present they may be poorly sampled. Inclined boreholes may provide a more complete characterisation of fracture distributions and flow at contaminated Chalk sites, however, this approach is largely untested in the Chalk. Data derived from scan-line surveys, as described in Section 5, may also contain significant biases. However, the most significant uncertainty in any fracture survey is the degree to which measurements of fracture porosity obtained at a surface exposure or from borehole investigations are representative of the volume of rock mass under consideration. Generally the 'sampled' volume is only a very small fraction of the volume of interest. Therefore it is necessary to identify methodologies that provide a robust method of extrapolating outcrop and borehole data to the scale of the rockmass under investigation.

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