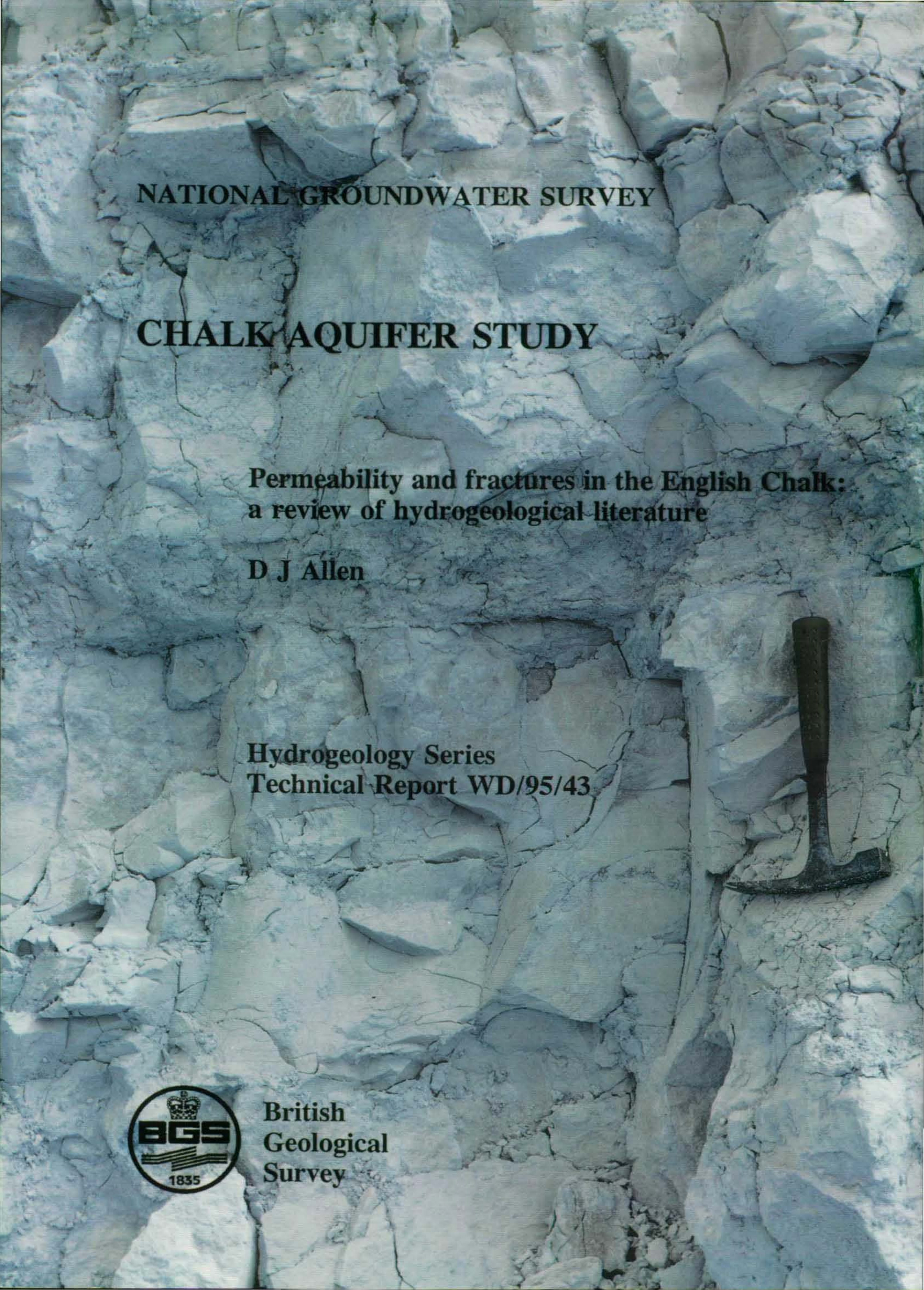

NATIONAL GROUNDWATER SURVEY

# CHALK AQUIFER STUDY

## Permeability and fractures in the English Chalk: a review of hydrogeological literature

D J Allen

Hydrogeology Series
Technical Report WD/95/43

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 Keyworth, Nottinghamshire British Geological Survey 1995

BRITISH GEOLOGICAL SURVEY

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## FOREWORD

The purpose of this report is to provide a review of the hydrogeological literature concerning the hydraulically significant fractures in the Chalk aquifer in England. The review discusses only the effect of the fractures on the permeability of the aquifer; it does not address the question of storage, nor the properties of the matrix.

The report charts the evolution of ideas regarding the nature, occurrence and causes of hydraulically significant fractures in the Chalk and attempts to summarise the present state of knowledge concerning the fractures, noting where gaps in understanding exist. Finally suggestions are made concerning future research.

## CONTENTS

## 1. Early Ideas

It has long been recognised that water in the Chalk flows primarily through fractures, and that the intergranular permeability is low. As Morton (1929) put it "The capillary nature of the interstices in Chalk produces so great a frictional resistance to the passage of water that the yield of wells and galleries is largely dependent on the frequency, size and distribution of the fissures..." and, commenting on the problems of well siting, "The engineer at the bottom of a shaft sunk under these (unfractured) conditions is a very Tantalus, with abundance of unavailable water on every side within his touch."

Woodland (1946), in a study of the hydrogeology of part of East Anglia, recognised the fundamental importance of fractures to the transmissivity of the Chalk. He considered that structure had some control on transmissivity and made the observation that fractures tend to be open in anticlinal areas and closed in synclinal areas (citing in particular the improved yields of anticlinal belts in Suffolk[1]). However he considered that, in general, solution was the main factor in the development of permeability. He suggested that "It is reasonable to assume that originally the Chalk had a more or less uniform permeability, but as topographical evolution develops, particularly after other deposits of varying permeability had been laid down on the formation, selective differentiation took place. Where soft water (i.e. rainfall) gained easy access in large quantities to the beds the amount of solution was large and so the cracks were widened". Woodland suggested that every million gallons of rainwater passing through the Chalk can remove 1.25 tons of calcium carbonate in solution, and so the potential for solution enlargement of fractures is considerable (although this would be reduced somewhat by compaction).

He pointed out that most of the transmissivity of the aquifer was provided by the upper 50 or 60 metres, and that (apart from the Chalk Marl) the transmissivity was relatively independent of stratigraphic horizon, except for beds such as the Totternhoe Stone and Melbourn Rock.

Woodland provided a map of borehole productivity, based on specific capacity, and from it made several observations.

1) The best yields are obtained in river valleys, particularly where the Chalk is exposed, or is overlain by glacial sands rather than by boulder clay. Woodland suggested that the reason for this enhanced transmissivity (although he did not use the term) was that in such areas acidic recharge could easily penetrate the Chalk. Woodland also noted that yields could be high even where the drift was thick, if the Chalk lay beneath a buried river channel. Again he invoked the solution properties of percolating waters as the cause of the enhanced transmissivity - in this case from glacial water flowing in the channels.

[1] It should be noted that while the connection between transmissivity and structure has subsequently been supported by several authors, Woodland's Suffolk example is now in doubt.

2) Beneath the Tertiary cover Woodland found that the best yields were still along the lines of main valleys, with a reduction on the interfluves. He speculated that this resulted from important fractures following the valleys and enlarged by solution.

3) Woodland found that the poorest yields were given by Chalk under thick impermeable cover - either thick Boulder Clay, or beneath the London Clay. Another low-yielding area was the synclinal belt of central Suffolk.

It is evident therefore, that by 1946 many of the current concepts regarding the distribution of transmissivity in the Chalk, and its reliance on fractures, were established, particularly by Woodland. He not only pointed out the topographic distribution of permeability - with the highest values found in major valleys - but he also noted the general restriction of high values to shallow depths, and the broad independence of permeability on stratigraphic horizon. His hypothesis of solution enhancement of fractures as the main cause of enhanced permeability in the Chalk has been taken up by several workers subsequently, and is now a commonly held idea.

## 2. Regional variation in transmissivity

Ineson (1962) used a method of transmissivity estimation based on the prediction of transmissivity from specific capacity data[2] to produce maps of transmissivity variation over the Chalk. The most pronounced feature of these was the correspondence between areas of high transmissivity and river valleys, with particularly high values at valley confluences. He suggested that the effect persists down dip, even when the Chalk is covered by younger deposits. In East Anglia Ineson found that enhanced valley permeability also occurred where the Chalk was covered, and in these cases the permeable zone was broader than in Chalk valleys at outcrop.

Ineson's findings were supported by a Water Resources Board investigation in the London Basin (WRB, 1972). This showed high transmissivity in the valleys, with the highest values in the unconfined Chalk, generally decreasing towards the axis of the syncline

As a result of the Phase I investigations of the Thames Groundwater Scheme, Owen and Robinson (1978) produced a transmissivity contour map for part of the Upper Thames Valley which was based on the interaction of four parameters; distance from a main flow concentration valley, depth to water table, saturated thickness of the aquifer and the proportion of the effective aquifer in the lower Chalk. The method was found to produce contours which agreed reasonably well with field data, and which the authors felt was applicable to areas in the same region with limited data.

In 1979 Morel, in a report describing a mathematical model of the Chalk in the Upper Thames basin, examined some of the possible controls on transmissivity and productive fractures in the Chalk. He applied statistical analyses to the empirical rules for transmissivity estimation used by Owen and Robinson (1978) and found that most of the areal variation could be explained by using the distance of the pumped boreholes from valleys, although this did not appear to explain well the transmissivities obtained from observation boreholes. Morel found that the depth to water table was not a statistically significant control.

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[2] In 1959 Ineson produced a study of the 'type' behaviour of Chalk wells, followed shortly after by an investigation of the transmissivity variations of the southern Chalk (Ineson, 1962). Ineson studied 200 yield/depression curves for Chalk wells and found that 75% appeared to follow type curves. The other 25% of wells followed 'breakaway curves' with extra drawdown to the predicted type curve beyond a certain point. Ineson attempted to correlate transmissivity with his type yield/depression curves for a particular (10 ft) drawdown. He then argued that, given a single yield/depression point for a well (corrected for borehole diameter), the 10 ft drawdown could be estimated from the appropriate type curve (assuming non-breakaway behaviour) and the transmissivity could then be estimated.

## 3. Variation of permeability with depth

The studies outlined in the previous section used a mainly statistical approach for elucidating the hydraulic properties of the Chalk by comparing the responses to pumping of many boreholes spread over a large area with the aquifer's geology and structure. While this could provide a broad insight into the regional geological controls on transmissivity (and, by implication, on fracture distribution) it indicated little about the local controls on such hydraulically active features, or their number and frequency.

Some light was thrown on this by the work of Tate and others (Tate, Robertson and Gray, 1970), who used electrical resistivity logging to identify major lithostratigraphic features, and a combination of temperature, fluid conductivity and flowmeter logs to determine inflow levels. They showed that the major levels of inflow in a borehole near Newbury occurred at depths to 30 m, with minor flows associated with the hard beds at the base of the Upper Chalk at a depth of 112 m.

Borehole geophysical techniques were used extensively to determine flow levels in the Chalk in the Thames Groundwater Scheme study reported by Robinson (1975). Robinson studied the results of suites of logging involving some or all of electrical, flow, fluid conductivity, fluid temperature and closed circuit television techniques which were carried out in many production and observation boreholes in the upper Thames Valley. After analysing the results Robinson's main conclusions were:

i) that in the unconfined aquifer 90% of the major yielding fractures lay between rest water level (rwl) and 60 m below rwl, although minor fractures were noted throughout the depth of the boreholes. Assuming rwl to be 10 m below the ground surface this gave a useful aquifer depth of 70 m . A thickness of 70 m was also found to characterise the confined aquifer.

ii) a non-linear decrease of productive fracture occurrence with depth was noted in the unconfined aquifer. Productive fracture density peaked at around 20 m below ground level, but Robinson considered that in reality the peak would be shallower than this, in the zone of water table fluctuation, where logging was not always possible because of the drawdown caused by pumping.

iii) most of the fractures seen on the TV logs were near-horizontal features (interpreted as bedding-plane fractures). Vertical features were thought to be common, but would be uncommon in vertical boreholes.

iv) the location of productive fractures was considered to be a function of their proximity to the zone of groundwater movement and not a function of lithology, the exception being the Chalk Rock and resistivity marker band 'F' (as long as these were not below a depth of 90 m). Both the Upper, Middle and Lower Chalk (except the lowest 30 m of the latter) could yield water from fractures if sufficiently near the surface.

Owen and Robinson (1978) explained a commonly noted phenomenon whereby drawdowns in pumped wells increased at rates greater than would be predicted by standard theory. They postulated that the increased drawdown responses were caused by a combination of lateral decreases in transmissivity (away from valley bottoms) and by dewatering of productive fractures as the drawdown increased.

In 1974 Foster and Milton (Foster and Milton, 1974) reported on hydrogeological work undertaken at a site at Etton, in the East Yorkshire Chalk. Detailed pumping tests were carried out which showed that a high proportion of the transmissivity of the aquifer (approximately 50%) was given by fractures in the zone of water table fluctuation - a zone 7 m thick. Other flow zones were shown by geophysical logging to extend from around 30 m below the highest rest water level to a depth of around 50 m. It was speculated that the upper flow zone was the result of long-term circulation and solution, possibly with transmissivity increasing towards discharge areas. Similarly the authors suggested that the lower flow zones could have been caused by solution during periods in the Pleistocene when base levels were lower; alternatively, possible lithological control was suggested.

Headworth, Keating and Packman (1982) suggested that a zone of high transmissivity and storativity around 6 m thick existed at the water table in the Candover catchment. The authors speculated that the origin of the zone may have been during a period when water levels were maintained at a high level by a barrier that was subsequently breached.

Other studies in the 1970's contributed to the growing evidence that the hydraulically active fractures in the Chalk were generally independent of gross stratigraphy, but were controlled mainly by topographic factors. Thus in the Great Ouse Scheme in East Anglia it was found that 90% of borehole yields were derived from the upper 60 m of the Chalk (Anonymous, 1972), and in the Upper Wylye Investigation in Wiltshire,most water was obtained from the upper 35 m of the aquifer (Anonymous, 1973).

**Productive fracture geometry**

There has been little published work on the characterisation of fracture geometries in onshore Chalk in the UK, and even less information concerning those fractures which are significant in the transmission of water. Hydrogeologists have tended to regard Chalk fracture geometry in very general terms. For example Price (1987) suggested that Chalk fractures could be considered as having two components, which he termed primary and secondary, where the primary set are relatively ubiquitous but have narrow apertures, whereas the secondary features are wider, but more local. He suggested that generally there are three orthogonal sets of joints, one of which is approximately parallel to the bedding, and referred to a detailed study of the Middle Chalk at Mundford, in Norfolk (Ward et al, 1968) where the joint spacing exceeded 0.2 m, reducing as the Chalk became more weathered to around 0.01 m, before the Chalk became structureless.

## 4. Chalk fracture hydraulics

In order to understand and predict the hydraulic behaviour of fractures in the Chalk it is necessary to understand their geometry, and in particular such factors as effective fracture aperture, spacing and degree of interconnection. As noted in the previous section there is very little published information available on these matters, and in general hydrogeologists have tended to invert the argument, making broad inferences about possible fracture apertures from hydraulic data.

When considering fracture hydraulics in the Chalk, British hydrogeologists have all used the simple equation governing flow in a smooth parallel-sided fracture. In terms of the hydraulic conductivity of the fracture this is:

$$K = \frac{\rho g b^2}{12\mu} \qquad \text{(i)}$$

Where:

- $K$ = fracture hydraulic conductivity (m/s)
- $b$ = fracture width (m)
- $\rho$ = density of water (999.7 kg/m$^3$ at 10 C)
- $g$ = gravitational acceleration (9.8118 m/S$_2$)
- $\mu$ = dynamic viscosity of water (1.3037x10$^{-3}$ Ns/m$^2$ at 10 C)

Using the appropriate values shown above, equation (i) reduces to:

$$K = 6.27\times10^5 b^2 \qquad \text{(ii)}$$

If K is in metres per day and b is in millimetres, then equation (ii) becomes:

$$K = 5.42\times10^4 b^2 \qquad \text{(iii)}$$

Some idea of the effects of fracture opening on hydraulic conductivity and transmissivity are given below (to two significant figures):

| Aperture<br>mm | Hydraulic conductivity<br>m/d | Transmissivity<br>m$^2$/d |
|---|---|---|
| 0.1 | 540 | 0.05 |
| 1 | 54 000 | 54 |
| 5 | 1 400 000 | 6 800 |

These figures are purely theoretical, taking no account of roughness, tortuosity or channelling, which will undoubtedly reduce the actual hydraulic conductivity of a real fracture compared with the figures presented above. However the essential point is that fracture permeability increases rapidly with increasing fracture aperture, and only relatively narrow fractures need to be invoked to account for high transmissivities.

Foster and Milton (1974) argued along the above lines, showing the significant effect of increasing fracture width on transmissivity. They also estimated that non-laminar flow would be unlikely to develop in fractures with widths of less than 2-3 mm under most natural groundwater flow conditions.

Price (1987) suggested that a distinction could be made between ubiquitous narrow fractures, which he termed primary fractures, and solution-enlarged fractures, which he termed secondary fissures. From the limited available data Price suggested that the primary fractures had a typical hydraulic conductivity of the order of 0.1 m/d and contributed a transmissivity of around 20 $m^2/d$ to the aquifer, while the secondary fissures essentially gave the balance of observed transmissivity (often more than 1000 $m^2/d$ where the Chalk is a good aquifer) - the contribution from the matrix being negligible. Price noted that the description of the Middle Chalk at Mundford (Ward et al, 1968) would imply theoretical fracture apertures of 55-60 $\mu m$ for an average hydraulic conductivity of 0.1 m/d.

A recent study by Younger (1995) used a suggested connection between Radon production and fracture aperture to estimate mean fracture apertures at several sites in the London area and Berkshire. Assuming a parallel plate fracture model, a mean aperture of 0.45 mm was calculated. From equation (iii) this leads to an estimate of 11 000 m/d or a transmissivity of 4.9 $m^2/d$ for each fracture[3]. From fracture surveys at several sites Younger estimated a mean fracture frequency of 9.4 per metre for the Thames area, which, for two orthogonal fracture sets with equal spacing and an aquifer thickness of 50 m would suggest a transmissivity of 4 600 $m^2/d$. This is of course a very crude calculation and is likely to be a significant over-estimate, given the assumptions (and of course the radon data were derived from wells, which were presumably in transmissive areas), but it might imply that significant contributions to transmissivity from the pervasive tectonic fractures should not be ruled out.

Direct evidence of the highly transmissive nature of some of the fractures in Chalk boreholes was given by Price, Robertson and Foster (1977), and Price Morris and Robertson (1982) In the earlier study the comparison of packer test and core analysis data from a cored Chalk borehole in Hampshire showed that the total permeability of the zones without highly permeable fractures was at least an order of magnitude higher than that given by core analysis. The permeability of the hydraulically active fractures was too high to be measured, but it was estimated that nearly all the transmissivity of the section tested was given by 12-17 % of the saturated thickness. In the later study, involving packer tests in a borehole at Totford in Hampshire, one fracture was found to have a transmissivity of around 500 $m^2/d$, or 60% of the total borehole transmissivity of around 800 $m^2/d$.

**Direct evidence of flow horizons - tunnels**

Apart from borehole results there is hardly any literature on direct observations of water movement in fractures. One report is that by C J Mustchin (1974) in which the construction of headings from wells at several sites in the Brighton area (made in order to intercept groundwater flowing out to sea) were described. Mustchin's relatively detailed report contains several points of hydrogeological interest.

[3] Unfortunately Younger's use of the equation is in error, giving values smaller by a factor of nearly $10^5$, and therefore his conclusions are not reproduced here.

i) The spacing of individual productive fracture was variable, but generally exceeded 20 m.

ii) Flow rates from individual fractures varied up to 6 Ml/d.

iii) Productive fractures were encountered both parallel to, and at an angle to, bedding were encountered, although the proportions at different orientations are unknown.

iv) The effect of channelling of flow in some fractures was noted, with flows from circular 'bores' recorded.

Such direct evidence of productive fractures is unfortunately extremely limited, but it does indicate that discrete, widely-spaced high permeability flow horizons may exist at depth in the Chalk (although it should be pointed out that Brighton may be somewhat unusual in having open fractures at greater depths than in other Chalk areas).

## 5 Controls on productive fracture development

Ineson (1962) suggested that the coincidence of high transmissivity with valleys indicated common causes, and that lines of structural weakness, assisted by fracturing caused by unloading, could be the link. Thus zones of structural weakness would not only form the basis of valley development, but would also provide an initial fracture system for groundwater flow. This fracture system would then be further (and continuously) enhanced by solution effects arising from variations in the $CO_2$ content of the water. Ineson further argued that the increased transmissivities of valleys covered by post-Cretaceous deposits are also the result of initial tectonic fractures enlarged by solution. However he noted that, in general, transmissivities fell as overburden increased, as a result of increased compaction.

Ineson argued that anticlinal and synclinal structures also exerted an influence on Chalk transmissivity, with anticlinal features leading to enhanced values of transmissivity, and synclines causing lower values. He argued that these effects could be detected in both confined and unconfined Chalk. He also suggested that faults would tend to provide barriers to flow in the Chalk, as a result of fault gouge.

Ineson commented on the importance of Chalk lithology as a control on Chalk permeability noting that hard bands, such as the Melbourn Rock or Totternhoe stone, have increased permeabilities as a result of associated fracturing. Also he pointed out that the Chalk matrix, while not directly contributing to the permeability of the Chalk, had a role in providing water to the fractures.

The argument for the control of transmissivity in the London Basin by both structure and solution effects was supported by the Water Resources Board investigation in the early 1970's (WRB, 1972). The results of this study indicated high transmissivity values in the valleys, with the highest values in the unconfined Chalk, generally decreasing towards the axis of the syncline. The study supported Ineson's ideas concerning structural control, postulating high transmissivities in anticlinal features and lower values in synclines, and also supported the finding that zones of high transmissivity associated with valleys could extend under Tertiary cover. This last effect was explained as due to fracture development as overburden was removed in valleys by erosion, followed by concentration of flow under the valleys vertically through the overlying Tertiary strata.

Robinson (1975) argued on the basis of the Thames Groundwater Scheme (Phase I) results that, although the Chalk is fractured throughout its thickness, only those fractures relatively near to the surface have been enlarged, by solution. When infiltrating water reaches the water table it moves from recharge to discharge zone via a relatively thin 'skin' of high permeability, while fractures at greater depths are kept closed by overburden pressures. The effect of overburden stress also results in enhancement of fractures by solution in the upper part of the confined aquifer being inhibited, resulting in lower values of transmissivity. Robinson also noted that there appeared to be a correlation between transmissivity, as measured by pumping tests, and the distance of the borehole from the nearest major river valleys.

Connorton (in an appendix to Robinson [1975]) argued that the ability of groundwater to dissolve Chalk depended on the partial pressure of $CO_2$, which would decrease exponentially with time. Assuming the partial pressure of $CO_2$ in waters entering the Chalk to be independent of location, Connorton argued that waters entering the aquifer on interfluves would have little effect on fracture enhancement, because much of the ability of the water to dissolve chalk would be exhausted in the unsaturated zone. However near valley bottoms infiltrating waters would quickly enter the saturated zone where their aggressive properties would enlarge fractures.

Morel (1979) argued that any model of the Chalk in the Upper Thames Basin would have to account for the following:

The vertical decline of productive fractures with depth.

The decline of transmissivity and storage coefficient with falling rest water level.

The significant correlation between pumping test values of transmissivity and distance from main valleys, and the lack of correlation between transmissivity and depth to water table in the unconfined Chalk.

The relative lack of variation in transmissivity in the confined centre of the basin, compared with the large variation in the unconfined aquifer.

The presence and distribution of dry valleys.

Morel argued that there were problems with the Connorton model of Chalk solution because it was likely that infiltrating waters in the Chalk would become saturated with respect to calcite before they could enter the saturated zone, and that the lack of correlation between saturated thickness and transmissivity meant that the model was unlikely to have been operating while the water table was at present levels. On the other hand Morel noted that high bicarbonate levels in the Chalk of the South Downs found after heavy rain (Downing, Smith and Warren, 1978) suggested that rapid recharge could lead to significant carbonate solution. He also noted that there was evidence for the production of $CO_2$ from humic decay in the Carboniferous Limestone of the Mendips (Atkinson, 1977) which could assist with solution in the Chalk - although Morel believed that this effect would be small because the smaller fractures in the Chalk could transport less humic material.

Morel also argued that the zone of productive fractures in the confined Chalk was difficult to explain by Ineson's mixture of structural controls, the effects of unloading, and solution because the zone was consistently restricted to the upper 60 m or so of the Chalk, whatever the thickness of overburden. Also the low transmissivity of the southern limb of the London Basin syncline would indicate more restricted northerly flow under the Tertiary cover, and so if solution was important, lower transmissivities in the confined aquifer to the south of the basin axis would be expected, which, he suggested, is not the case[4].

[4] In fact, contrary to Morel's assertion, there is evidence that an area of low permeability exists in the confined Chalk near to the narrow southern outcrop, to the north of Guildford. However this is ambiguous evidence, because the area is deeply buried, and the low permeability may be associated with fracture closure by overburden stress,

Morel argued that, given the above, the combined effects of differential loading and solution were inadequate to explain the transmissivity variations of the Upper London Basin Chalk, and he suggested that the productive fractures were formed in unconfined conditions around the Cretaceous/Tertiary boundary, and Miocene-Pliocene Periods. He considered that the time following the glacial periods was too short to have allowed significant changes in the hydraulic properties of the Chalk aquifer.

Morel suggested that the present position of the water table in the Chalk is controlled by the inherited productive fracture distribution, with groundwater levels falling to the lowest level consistent with the transmissivity necessary to transport the throughflow of groundwater. Water levels therefore tend to be kept within the narrow zone of high transmissivity in the upper part of the aquifer.

Price (1987) suggested that a theory of solution-enhancement developed by Rhoads and Sinacori (1941) involving the formation of a 'master conduit' caused by the concentration of flow towards the river valleys might be applied to the Chalk (it had already been invoked by Rhodda, Downing and Law [1976] for the Carboniferous Limestone). Such a feature - possibly a set of solution-enhanced fractures rather than a single 'conduit'- would, once formed, tend to control the position of the water table, and Price cited the case of the Candover Valley (Headworth, Keating and Packman, 1982) as supporting evidence.

Price also argued that the solution enlarged fractures could have been created in the period since the last glacial recession, (although there were several broad assumptions in his argument).

Younger (1989) argued that in the Thames valley periglacial effects were very important in the development of productive fractures. His argument was based on several lines of evidence.

Younger postulated that, on the basis of work at several sites in the Thames valley, no correlation existed between fracture frequency and distance from the valley. He therefore argued that the general increase in permeability of the Chalk in valleys was caused by the localised enlargement of existing bedding plane fractures (seen on Closed Circuit TV in boreholes) in regional systems by solution, and not by increased tectonic fracturing in valleys. He disputed Ineson's suggestion that unloading in valleys would cause more fracturing, by arguing that the depth of burial, and therefore the effect of subsequent unloading, was insufficient.

Younger's second line of evidence was the existence of 'putty chalk' in the Thames Valley. He noted that while boreholes in the middle Thames Valley often showed high transmissivities on pumping, sometimes boreholes encountered low permeability putty chalk in their upper sections. This putty chalk may be thick (up to 48 m at one site) and has a low hydraulic conductivity (around 0.2-2 m/d), and its effect, in the often highly permeable upper section of the borehole is to greatly reduce the transmissivity of the aquifer. Younger argued that putty chalk was formed under periglacial conditions. It often occurs on interfluves at the top

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rather than simply by lack of recharge and subsurface circulation.

of the Chalk, where it has its origin in the freeze-thaw zone above the permafrost. In the Middle Thames Valley putty chalk is found below gravels where the valley is widest. Conversely the highest-yielding boreholes were to be found where the valley is narrow.

Younger's model to explain the above observations was based on periglacial effects on the Chalk during the Devensian. He argued that in the interfluve areas all groundwater circulation was prevented below perennial permafrost table (a depth of a few metres). Above the permafrost mechanical weathering could occur (freeze/thaw) with some solution in summer. In dry valleys permeability would be enhanced by cryoturbation and seasonal taliks (zones of unfrozen material).

In the main valley, where it was narrow, there would be a perennial talik, where discharging groundwater would inhibit the formation of permafrost, and enable solution enlargement of the fractures to occur[5].

Where the main valley was wide the discharge zone would be more diffuse and taliks would not be so well developed. Here freeze-thaw might lead to formation of putty chalk, and the solution enlargement of fractures would be less.

Younger argued that the Connorton model of solution, while attractive, was problematic in that it could not operate during the Devensian since the permafrost would have restricted flow and $CO_2$ consumption. It was debatable whether the time since the Devensian (10 000 years) was long enough for the solution mechanism to operate.

Younger rejected Morel's hypothesis that the productive fractures were formed before the deposition of Tertiary cover. His argument was in essence a rejection of Ineson's work, with the contention that there was no good evidence for valleys following zones of structural weakness, and that where high permeability continuations of river valleys under Tertiary deposits are found, the cover is permeable - except where the Chalk is deeply confined when the permeability is low.

**Lithological Controls on fractures**

Mortimore (1993) has suggested that the aquifer properties of the Chalk are strongly controlled by lithology. His argument may be summarised as follows;

i) Marl

Mortimore cited evidence of perched water horizons on marl bands, and marl seams with solution enlarged fractures along them. He argued that where marls or clay-rich chalk bands alternate with harder limestone beds sub-horizontal fractures are likely to be found in the marls, with vertical fractures in the chalk. One example that he gave is at Eastbourne where the clay-rich Plenus Marls are overlain by the hard Melbourne Rock which is extensive

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[5] This concept does raise some questions. For example where would the talik water originate if the interfluves were covered in permafrost? Also would not this discharge water be saturated with calcite and therefore relatively unaggressive? Finally would not the vertical flow tend to enlarge vertical rather than horizontal fractures?

fractured by steeply inclined conjugate joints. The Plenus Marls have dissipated stresses sub-horizontally causing the fractures in the Melbourne Rock to open. The water-bearing fractures at the Plenus Marls-Melbourne Rock have been exploited by water-collecting adits.

ii) Soft and hard chalk

Mortimore suggested that in the Anglo-Paris Basin the soft to medium-hard chalks (e.g. the Seaford Chalk in Sussex) tend to have regular orthogonal joints and they tend to have better developed karstic systems than the softer chalks. Very soft chalks (such as the late Cenomanian White Bed of the North Downs) are irregularly fractured, and the fractures may be sealed by chalk-putty. He implied that transmissivity may be a function of chalk hardness.

Mortimore concluded with the hope that, "by fixing the altitude and the exact stratigraphy of the saturated rock column, the relationship between lithology and the key water-bearing horizons can be established".

Geophysical logging techniques provide an opportunity to examine the possible correlation between Chalk lithology and productive fractures. For example Buckley and others (1989) have shown from borehole logging evidence that the location of hardgrounds may control the levels of solution enhanced fractures for an area in East Anglia. It may be that other low permeability horizons, such as flints or marls may provide similar constraints on flow horizons.

**Discussion**

The evolution of ideas outlined above has resulted in a certain consensus amongst hydrogeologists concerning the importance and general distribution of productive fractures in the Chalk, with less agreement with regard to their origin.

It has long been accepted that fractures dominate the transmissivity of the Chalk, and that the transmissivity of the aquifer is higher in the valleys than on the interfluves. It therefore follows that there are generally more or larger fractures in valleys than on interfluves. It is also accepted that, in general, the productive fractures are restricted to the upper few tens of metres of the aquifer (50 m is commonly used), whether unconfined or confined. Deeper productive fractures are known, but these are regarded as the exceptions proving the rule.

There is a range of opinion regarding the causes of, and controls on, the productive fractures. It is generally accepted that they result, in the main, from the enlargement of pre-existing fractures by solution, but there is a range of opinion concerning the relative importance of tectonic effects - possibly assisted by overburden removal - compared with solution effects in the formation of the resulting permeable features. The importance of solution has been universally acknowledged, with no hydrogeological writer supporting the idea that productive fractures are solely formed by mechanical effects. However Woodland, Ineson and Morel have all taken the view that valleys are likely to be controlled by structure, and such 'zones of weakness' also provide the starting point for high transmissivity zones, later to be further enhanced by solution. At the other extreme Younger proposes the preeminence of solution, arguing that there is no evidence for 'zones of weakness' but postulating instead the effect of periglacial conditions as the main control (in the Thames Valley). A third facet to the tectonic-solution discussion has been added by Mortimore who has shown both that the Chalk is more lithologically variable than was previously thought, and that such variations may be very significant in determining the type and location of the productive fractures. Direct evidence of lithological control on fracture horizons has been provided by Buckley and others.

There is little agreement on the timing or the timescale of the production of the hydraulically significant fractures. Some writers (eg Price) have argued that the period since the Devensian (c. 10 000 years) is sufficient for solution effects to have enlarged pre-existing fractures, while Younger proposes the period of periglaciation was sufficient, while in contrast Morel suggests that the productive fracture system was essentially complete before the Tertiary strata were laid down.

## 6. The Chalk as a karst

The above review is essentially a hydrogeological view of the Chalk, in which it is considered as an aquifer amenable to normal hydrogeological techniques, such as pumping tests and packer tests, and where concepts such as transmissivity and permeability have a well defined meaning. However, seen from a different standpoint, as a potentially karstic material, the way in which fractures are viewed as contributing to the water-bearing properties of the Chalk may be seen in a somewhat different light.

### Features of karst

The term 'karst' is not precisely defined but is associated with terrain which has distinctive landforms and hydrology by virtue of a combination of high rock solubility and well developed secondary (fracture) porosity. Typical karst features are sinking streams, caves, enclosed depressions, fluted rock outcrops and large springs, as exemplified by the Karst district on the border between Italy and the former Yugoslavia.

In hydrogeological terms the main attribute of karstic aquifers is that groundwater - recharged either from sinking streams or by more diffuse infiltration - is to a significant extent concentrated in, and flows rapidly through, a network of fractures, conduits and caves which have been enlarged by solution. Flow tends to be directed to discrete discharge areas in the form of single springs, or spring groups. It is axiomatic that for such a karstic hydrogeological system to be developed in an aquifer the rock must be sufficiently soluble, adequate recharge must occur over a suitable time period for conduits to be produced, and there needs to be enough topographic variation for adequate head gradients to be imposed on the aquifer. It also follows that karstic systems are dynamic, with solution (and re-precipitation) processes affected by a variety of controls such as head gradient, temperature, and water chemistry.

Atkinson and Smart (1981) have suggested that the use of the tem 'karstic' with respect to groundwater flow should be restricted to solution enlarged features in which the flow regime is turbulent. They argued that it is possible to envisage a spectrum of aquifer types from the wholly karstic in which all groundwater flow and storage occurs in solution enlarged 'conduits' to the non-karstic fractured aquifer, in which solution-enlarged fractures are common, but where turbulent flow in conduits is a rarity. They suggest that British limestone aquifers can be arranged along such a spectrum from the Chalk, via the Jurassic limestones of the Cotswold hills and Lincolnshire, to the Carboniferous Limestone. In their view the Chalk is predominantly non-karstic, although solution-enlarged fractures with laminar flow are very important.

### The significance of karstic features in the Chalk

The extent to which groundwater flow in the Chalk can be considered to be karstic is of great significance to its role as an aquifer. The more karstic an aquifer is, the less it is amenable to analysis by traditional hydrogeological techniques. For example standard pumping test analysis assumes that an aquifer can be considered to be homogeneous, isotropic, and of uniform thickness over the area influenced by the pumping test. Therefore in general terms the more that flow in the Chalk is restricted to a few fractures, the less appropriate will be the standard methods of analysis.

Also, since the radius of influence of a pumping test varies as $(T/S)^{1/2}$, then for the Chalk aquifer, with generally high values of T and low values of S, a large radius of influence may be expected. For a test lasting a week or more the radius of influence could exceed 2 km. This could encompass chalk with a wide range of permeability and can cause problems with the interpretation of the test data (as, for example was pointed out by Owen and Robinson [1978]).

The degree to which flow may be considered to occur in a relatively limited number of solution enlarged fractures is crucial to understanding how pollutants may travel in the saturated zone. Where flow is significantly affected by such features the possibility arises of rapid, relatively unmodified transport of pollutants between a source and a discharge point. This could occur without the Chalk being conceived as truly karstic (in the sense of nearly all flow being concentrated in a few major conduits) but because sufficient laterally persistent hydraulically active (and to an extent hydraulically separate) fracture systems exist to enable rapid flows to occur.

The concept that fracture sets may act independently in a hydraulic sense appears to have been in existence for over half a century. As Morton (1929) put it "Experience in sinking wells and driving adits in the Upper Chalk formation teaches us that water is mainly obtained from the fissures and that even in closely adjacent fissures the pressure may vary considerably". Of course Morton's statement may not refer to actual head in the fracture, (but rather the perceived pressure at a well-face, involving various head losses), but there is evidence from tracer tests of fracture sets behaving independently (see below), and anecdotal evidence of independent fracture behaviour from water level data.

**Surface karstic features**

Surface karstic features such as solution pipes, swallow holes and dolines are widespread on the Chalk outcrop. Edmonds (1983) examined the spatial distribution of these features and concluded that possible factors controlling their distribution included proximity to the edge of overlying Tertiary deposits, lithology of the Chalk and overlying deposits, Chalk structure and the effects of glaciation. However the relationship between surface karstic features and the development of karstic-type permeability in the aquifer is unclear.

**Subsurface karstic features - tracer test evidence**

Subsurface karstic-type flow has been investigated at several sites in the Chalk by means of tracer tests, some of the most prominent examples of which are given below.

One of the best known sites in the Chalk of swallow hole activity is at Water End in Hertfordshire, where the Mimmshall Brook, a headwater of the River Colne, disappears at certain times of the year into a swallow hole complex. Tracer tests have shown that these recharging waters travel towards the River Lea Catchment at velocities of up to 5 500 m/d (Morris and Fowler, 1937).

Atkinson and Smith (1974) reported a tracer experiment in the Havant-Bedhampton area. Rhodamine WT dye was pumped into a swallow hole for three days, and the travel time to its emergence at the Bedhampton spring at a distance of 5.75 km was 62.5 hours, corresponding to a velocity of 2 200 m/d (peak concentration). From calculations involving the quantities of flow and the hydraulic gradient Atkinson suggested that the fracture was the equivalent of a pipe 0.74 m in diameter (although in reality several features would probably be involved). Price (1987) suggested that in an ideal case (a plane parallel fracture with no roughness or channelling) a fracture of only 4.5 mm width, and with a transmissivity of 5 000 $m^2/d$ could carry the observed flow.

Banks, Davies and Davies (1995) reported a tracer test in Berkshire between a swallow hole and a spring 4.7 km away which indicates the highest velocities yet observed in the Chalk, 5 800 m/d for peak concentration and 6 800 m/d for breakthrough. The authors suggest that little attenuation occurred as the tracer moved from the sinkhole to the spring. By using Price's (1987) method the authors calculated that a single fracture of opening 5.4 mm could theoretically be sufficient to represent the fracture system.

These tracer tests, and others, show that fast preferential flow routes (or karstic flows) do occur in the Chalk, and are commonly associated with the proximity of Tertiary cover. However what is not known is how common such behaviour is. Are these special cases on which interest has been focused because of obvious features such as sinking streams and resurgences, or do they represent only the most apparent examples of a more widespread phenomenon?

Unfortunately, little tracer work appears to have been carried out in Chalk at arbitrary points unconnected with obvious karstic features. One such experiment was undertaken at the M1/M25 motorway intersection and was reported by Price, Atkinson, Barker, Wheeler and Monkhouse (1992). This area is close to the Chalk/Tertiary boundary and karstic features are common, but the studies were carried out in soakaways which were apparently unassociated with karstic features. Tracer studies carried out in soakaways at the motorway intersection showed that some tracer travelled rapidly to a pumping station (a distance of 3 km), with maximum recorded velocities in excess of 2400 m/d, but tracer recovery was very low, and it was thought that significant amounts were moving through fine fractures.

Another tracer study in Chalk apparently unassociated with karstic features was in East Anglia (Ward, 1989). In this study the tracers were injected into observation boreholes and their arrival at nearby pumped boreholes was observed. The main conclusion of the work was that the flow was dominated by microfractures with a range of sizes, rather than by a few discrete high permeability conduits.

**Conclusion**

Given the above evidence it must be concluded that there is as yet insufficient information to determine to what extent groundwater flow in the Chalk may be karstic - in the broad sense of there being significant quantities of flow through discrete transmissive fractures or fracture sets over scales of more than a tens of metres.

It is important to understanding the hydrogeological nature of the Chalk, and particularly to evaluating how pollutants may move in the aquifer, that this question is investigated, and this may involve using techniques more familiar to the karst hydrologist than to the hydrogeologist. Tracer testing has already become an established hydrogeological tool, but there are others (such as spring hydrograph analysis) which could be used to give insight into the hydraulic behaviour of the fractures.

## 7 Summary

The importance of fractures in Chalk hydrogeology has long been recognised, as has the importance - if not the pre-eminence - of solution enlargement of (predominantly bedding plane) fractures as the main agent of Chalk transmissivity enhancement. The distribution of the productive fractures with depth, with the majority being constrained within the upper 50 metres of the Chalk, and the areal distribution, with most transmissive fractures being found in valleys, is also almost universally agreed.

However there are major areas of uncertainty in understanding the origin and distribution of water-bearing fractures, for example:

i) The geometry of the original tectonic fractures before enlargement by solution is poorly understood.

ii) The relative contribution of these fractures compared with those enlarged by solution is poorly known.

iii) The mechanism for the enlargement of fractures by solution is not known, except in broad terms, nor is the relative importance of lithological control.

iv) The degree to which fractures or fracture sets act independently (in the sense of providing fast flow routes through the aquifer) is not known.

In order to throw some light on these matters it will be necessary firstly to integrate the hydrogeological and hydrochemical approach to the aquifer with the increasing understanding of its structure and geology, and secondarily to turn more to the hydrological techniques used by investigators of karst terrains to assess the importance of Chalk fractures on Chalk flow paths.

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