“The Effects of Fractures upon Vertical Dipole Flow and Tracer Tests in Porous Aquifers”

Dissertation submitted as part requirement for the Degree of Master of Science in Contaminant Hydrogeology

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Christopher George Pembroke certifies that all the material contained within this document is his own work except where it is clearly referenced to others.

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Abstract

The vertical Dipole Flow and Tracer Test offers many potential benefits as a tool to characterise fractured rock aquifers at contaminated groundwater sites. This project focuses upon investigating the influence of fractures upon the tracer breakthrough curves arising from Dipole Flow and Tracer Tests conducted in a fractured porous media. A modelling approach has been adopted, using the numerical model HydroGeoSphere to simulate tracer transport in dipole flow fields generated in 32 different fracture scenarios. This investigation focussed upon the influence of fracture location and fracture aperture upon the resultant breakthrough curves. The region of influence of the DFTT was found to be confined to a relatively short distance above or below the active chambers, whilst a fracture “blind-spot” of the DFTT was identified within the dipole flow field. The DFTT has been found to be sensitive to the location of fractures within the region of influence, with sensitivity increasing with aperture. The fracture aperture sensitivity limits of the DFTT are identified, both experimentally and theoretically, with both the probe configuration and aquifer matrix properties exerting a control upon this. A breakthrough curve interpretation approach is developed, incorporating the derivation of a “Shape Factor” as a single value descriptor of the curve, capable of distinguishing between fractures of different apertures. Subsequently an outline methodology is proposed, and practical considerations highlighted for the application of the DFTT to situations within the bounds of this initial research.

The potential of the DFTT as a valuable aquifer characterisation tool has been further developed by this project, which identifies the further research necessary to continue the progression of this tool towards real application.
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1. Introduction

1.1 Site characterization

A variety of toxic chemicals (such as fuels, fuel additives, solvents, pesticides, etc) play an essential role in the societies and economies of today, with their usage and diversity likely only to increase in the future. The production, use and disposal of such chemicals in the past and present however, has lead to soil and groundwater contamination, which may represent a threat, either currently or in the future, to a variety of receptors, including human health, groundwater resources or surface waters and associated ecosystems. The investigation, risk assessment and remediation design of contaminated groundwater sites requires knowledge of physical and chemical aquifer properties which control the distribution, fate and transport of contaminants. In contrast to the ground water resources industry, which primarily seeks to quantify aquifer parameters at a large scale, it is often the variations in certain aquifer properties which are of greater importance for contaminated land investigations. Hydraulic conductivity ($K$), for instance, exerts an important control over the distribution and transport of contaminants, since high $K$ zones may act as preferential mass flux pathways, whilst low $K$ zones may act as long term contaminant sources via back diffusion. Even the relatively homogenous sand aquifer of Borden, Canada has been found to exhibit vertical and horizontal heterogeneity in hydraulic conductivity resulting in calculated correlation lengths of only 0.12 and 2.8 m (Sudicky, 1986). The implications of this are that very intensive site investigation would be required to confidently understand the $K$ field for accurately predicting or modelling groundwater flow and contaminant transport, even for a relatively homogenous material.

1.2 Fractured aquifer conceptualisation

Geologically, fractured rock aquifers are highly heterogeneous media and consequently exhibit complex fluid flow and contaminant transport phenomena. For these reasons, it is recognised that such subsurface domains are challenging to characterise (US EPA, 2001). Therefore, the characterisation of fractured rock sites typically requires greater efforts than for unconsolidated porous media, due to the greater data volumes and different techniques required (US EPA, 2001; Thornton & Wealthall, 2008).
Two principal types of fractured rocks are defined here, categorised by the properties of the rock (termed the “matrix”), which are dissected by the fractures: Permeable matrix rocks (i.e. Chalk or Sandstone) and impermeable matrix rocks (i.e. Basaltic or Granitic rocks). For aquifers comprising the former, the permeability of the matrix relative to the bulk permeability of the aquifer has important implications for flow and transport. Analogous to the discussion of high and low \( K \) zones previously, a matrix of low conductivity relative to the bulk conductivity (total of matrix and fracture conductivity) may be hydraulically insignificant but may be highly important for solute transport in the fracture network due to back diffusion of solutes (i.e. Cretaceous Chalk).

Conceptualisation of fractured aquifers can be undertaken in various manners, dependent upon the nature of the media, scale of investigation and the aim of the exercise. The equivalent continuum approach considers the fractured aquifer as a porous medium, where flow and transport are described by bulk hydraulic properties. This technique can be used at a large scale, such as for water resources purposes (Nastev et al., 2004), whilst it may also be used for site characterisation at a smaller scale in highly fractured aquifers (Berkowitz, 2002). Criteria for determining the appropriateness of such an approach remain unclear, although the hydraulic response to a pumping test has been used (Podgorney & Ritzi, 1997). This method of assessment, however, failed to provide adequate differentiation in an evaluation of different conceptualisation approaches by Muldoon & Bradbury (2005), who also found that the carbonate aquifer under study could not be suitably considered as an equivalent continuum despite its highly fractured nature, likely due to effects from matrix storage. These assessments considered only the hydraulic responses, whilst solute transport was not assessed, which often reveals discrepancies between fractured rock breakthrough curves and those predicted using such an equivalent continuum approach (Berkowitz, 2002). Certain conditions for use of an equivalent continuum within a NAPL dissolution modelling scenario have loosely been identified (Rubin et al., 2004), but these provide little benefit for general characterisation of fractured rock sites.

An alternative suite of approaches consider the fracture network explicitly, either as a discrete entity (i.e. Hitchmough et al., 2007) or interacting with the matrix of the intact rock within which the fractures are set, this latter scenario commonly referred to as dual porosity (i.e.
Spence et al., 2005). This latter approach considers properties of both fractures and the matrix, which may respectively behave analogously to the high and low hydraulic conductivity zones of heterogeneous media as discussed previously. Whilst fractures may exert a dominant control upon fluid flow and contaminant transport, not all fracture elements will contribute uniformly to this effect. It is only a subset of the interconnected elements forming the fracture network which provide substantial hydraulic pathways (Morin et al., 1997; Wealthall, 2003). The interconnected fractures that form the significant pathways are therefore responsible for the migration and transport of contaminants; and it is such fracture elements that are crucial to characterise for investigation of contaminated fractured groundwater sites (US EPA, 2001; Hitchmough et al., 2005; Thornton & Wealthall, 2008).

1.3 Techniques for the characterisation of fractured aquifers

Characterisation of the fracture network may involve both geophysical and hydraulic techniques to resolve physical and hydraulic properties. An understanding of the physical properties of the fracture network, including orientation, spacing and trace length can be obtained from exposures as provided by quarries, cliffs, cuttings and tunnels (i.e. Wealthall et al., 2001; Wealthall, 2003; Hitchmough et al., 2007), although fracture apertures are not reliable due to enlargement following weathering and unloading. Oriented borehole cores and certain down-hole geophysics, such as acoustic or optical imaging techniques, are also routinely used in site investigations to provide data for such fracture parameters (US EPA, 2001). Such techniques, however, can only be used to infer connectivity of fractures from the statistics of trace length, spacing and orientation (Wealthall, 2003). They cannot provide direct hydraulic information or identify hydraulically significant fractures present at the specific site, neither can they provide reliable fracture aperture data; i.e. a large fracture may be unconnected and pinch out a short distance from the point of observation. The use of in situ hydraulic techniques is therefore required; a discussion of the available hydraulic techniques for characterization of fracture networks is now presented.

1.3.1 Multi-well tests

Forced-gradient tracer tests have been conducted within individual fractures and parallel fracture sets between boreholes to calculate transport related fracture parameters (Novakowski et al., 2004 & Himmelsbach et al., 1998, respectively). The use of such tests
predicates knowledge of the presence and location of such fractures however, presumably identified using alternative fracture characterisation techniques.

Pulse interference tests can be used to characterise properties of fractured aquifers between wells, based upon observation in a monitoring well of a pressure pulse established in an adjacent well (Hocking, 2002). The pressure pulse may be generated as a slug or short period of pumping, with the delay and shape of the response controlled by the hydraulic properties between the pulse source and observation wells (Stephenson & Novakowski, 2006). Inflatable packers may be used to isolate discrete zones in the source and observation wells, in order to improve the vertical resolution of the pulse interference tests (i.e. Hocking, 2002).

To produce data characterising the fracture network of an aquifer, the observation and pulse-source wells must be connected by the fracture network (Stephenson et al., 2006). Similarly to the individual fracture tracer-test of Novakowski et al. (2004) and indeed all multi-well tests, some level of an a priori knowledge of the scale of the fracture network is therefore seemingly required to appropriately locate boreholes. If the test is conducted in a fractured rock with a permeable matrix, the matrix must have a sufficiently low conductivity to allow the pulse interference test to prove fracture connectivity.

Multi-well techniques are perhaps not best suited for characterising fracture networks (i.e. for contaminated groundwater site investigations), since they rely upon connectivity of wells at a predetermined and essentially fixed scale.

1.3.2 Single well techniques

Single well techniques for characterising the fracture network overcome the fracture connection requirement of multi well tests, whilst also reduce the number of boreholes required to obtain fracture characteristics. This offers a substantial financial advantage, given the significance of site investigation expenditure associated with borehole drilling (US EPA, 2001). The scale of assessment of single well tests also differs from multi-well tests; the scale of the latter are physically constrained to the spacing of the wells, whilst single well tests are essentially unbounded. Operational parameters such as the utilised pumping rate, in addition to the properties of the fractured media, may however control the scale of assessment for single well techniques.
Pumping tests and slug tests can be conducted within boreholes and the results analysed to obtain horizontal hydraulic conductivity values, representing averages of the contribution from transmissive fractures and the matrix permeability. Similarly to the pulse interference test, inflatable packers may be used to allow pump, injection or slug tests to test discrete vertical intervals in the borehole (Brassington & Walthall, 1985; Hitchmough et al., 2004; Holloway & Waddell, 2008). High hydraulic conductivities indicate the presence of transmissive fractures within the tested interval, whilst inversely the absence of connected fractures is represented by low hydraulic conductivities approximating the matrix permeability (USGS, 1991). Since fracture apertures are still usually substantially smaller than the intervals tested using discrete packer tests, the hydraulic parameters calculated for each interval remain an average of the properties of the matrix and any fractures present, likely underestimating true fracture permeability (Thornton & Wealthall, 2008). The shorter the test zone interval adopted, the closer the test becomes to isolating and testing individual fractures (Muldoon & Bradbury, 2005), although this naturally increases the cost of the investigation. The data may still be used qualitatively to identify high flow zones (Thornton & Wealthall, 2008) and by overlapping the tested intervals down the borehole, the location of hydraulically significant fractures may be inferred to a smaller resolution than the test zone interval itself. From the inferred flow through a fracture, the “cubic law” can be used to calculate the “hydraulic aperture” of the fracture (equation 1):

\[
e = \sqrt[3]{\frac{12Q_f \mu}{\rho g w i}} \tag{1}
\]

Where \( e \) the hydraulic fracture aperture, \( Q_f \) is the flow rate, \( \mu \) fluid viscosity, \( \rho \) fluid density, \( g \) gravitational acceleration, \( w \) the width of the fracture and \( i \) the hydraulic gradient.

The single borehole dilution test can be used to measure a profile of specific discharge and hydraulic conductivity down the borehole, based upon the dilution of tracer concentrations within the well volume. A tracer is introduced into a defined well volume (either the entire borehole or a packer isolated section) to obtain a uniform tracer concentration. The subsequent decrease in concentration of the tracer is monitored, either at multiple levels throughout the column (Hiscock, 2005), or at a single point in an isolated section concurrently to mixing (Riemann et al., 2002). This latter approach was used to analyse a specific fracture
zone isolated by inflatable packers; whilst such a method could conceivably be repeated over multiple test intervals down a borehole, it would likely require considerable time to conduct. An alternative single well tracer test is proposed by Novakowski et al. (1998), where tracer is injected via a single well into the surrounding formation to create a radial source term, with the flow of this tracer (under the natural gradient) back into the same well monitored and interpreted to yield hydraulic and transport parameters.

Boreholes intercepting transmissive fractures may essentially act as hydraulic short circuits, with inflow from fractures at one level and outflow at fractures at another level. This generates a vertical velocity profile in the borehole water column, which can be measured using borehole flow-meters (Hess, 1982), allowing the location of transmissive fractures. Only the most transmissive fractures are likely to be identified, although if the hydraulic conditions are modified (i.e. from the ambient conditions to pumping induced stressed conditions) different fractures may become more transmissive and thus may be identified with this method (Lane et al., 2002).

A novel technique for identifying transmissive fractures within a borehole has recently emerged, involving the use of the “FLUTe” borehole liner system (Keller et al., 2006). General details of the FLUTe system also appear in Cherry et al. (2008). The rate at which the liner is introduced down the borehole is dependent upon the rate of displacement of water from the borehole into the formation, determined by the balance between the extra head inside the liner and the transmissivity of the remaining (as-yet unlined) borehole. The rate of the liner installation and head inside the liner are monitored, which can be used to calculate the change in transmissivity with depth (due to transmissive fractures becoming progressively sealed by the liner advance). This has been suggested to be advantageous over packer techniques, due to improved resolution, increased speed and reduced cost (Keller et al., 2006).

An advance to the single-well discrete zone packer tests is presented in Black (1994), termed the multi-packer connection test. This test is conducted in a single borehole with five packer isolated intervals, with the central interval subject to pumping (either extraction or injection) and the over- and under-lying intervals monitored for a response. The occurrence and magnitude of pressure responses in the isolated sections can be used to infer the presence and
significance of fracture connections between these isolated intervals. This technique remains a qualitative assessment of the fracture network, unless the drawdown data from the observation intervals can be interpreted with respect to a single identified fracture feature in the source zone (Black, 1994). Whilst this test allows inference of fracture connectivity in the vertical direction, a significant advantage over other tests, this is however not explicitly tested; therefore if horizontal fractures are hydraulically more significant, these instead will predominantly respond to pumping in the source zone and the vertical aspect of the fracture network will not be characterised. Additionally, this method can only infer fracture connectivity since it is based upon pressure heads and not mass transport, evidence of which could provide robust proof of connectivity.

1.4 Limitations
These techniques offer methods for characterising fractured aquifers, superior to basic porous media techniques, allowing the location of transmissive fractures intercepted by boreholes, and in some instances hydraulic parameters, to be inferred. They do, however, have one shared limitation: they predominantly hydraulically test (or are interpreted as testing) a volume of aquifer located radially (in the horizontal plane) around the tested interval. They therefore provide little insight to the vertically orientated aspects of the fracture network, either basic qualitative connectivity or quantitative parameterisation. One exception is the methodology presented by Black (1994), although this does not provide an explicit test in the vertical direction and cannot provide proof of connectivity. Additionally, fracture transport parameters, such as dispersion or channelized flow in fractures, cannot be assessed with such methods.

The vertical aspects of the fracture network is highly important for NAPL contaminants- both those denser (DNAPL) and lighter (LNAPL) than water. DNAPLs migrate downward under a density driven mechanism, whilst LNAPLs may penetrate fractures to significant depth below the water table if sufficient NAPL head is present at the surface of the rock aquifer. Due to the prevalence of such contaminants in the subsurface, techniques which are capable of investigating the vertical aspect of the fracture network are essential for the investigation, risk assessment and remedial design at such contaminated sites.
1.5 Vertical Dipole Tests

1.5.1 The Dipole Flow Test (DFT)

The Dipole Flow Test is a single-well hydraulic test originally proposed by Kabala (1993) for characterizing hydraulic properties of porous aquifers. The test uses three packers to isolate two chambers in the borehole, and establishes a “dipole-like” flow field in the aquifer by extracting water from one chamber at a constant rate and re-injecting in the other, a setup analogous to vertical recirculation remediation wells (Kabala, 1993). Figure 1.5.1 shows the general configuration and flow field of the dipole flow test. The two chambers are equipped with pressure transducers to monitor pressure changes (draw-down and draw-up) in the two chambers, from which aquifer properties can be interpreted. This can be undertaken from transient pressure changes using a type curve approach (Kabala, 1993) or analytically once steady state conditions have been reached (Zlotnik & Ledder, 1996; Zlotnik & Zurbuchen, 1998; Zlotnik et al., 2001).

Field studies of the dipole flow test have been conducted under various chamber configurations in porous media aquifers, with the horizontal (radial) hydraulic conductivities ($K_r$) obtained corresponding well (in terms of descriptive statistics and values) to results from grain size analysis, pumping tests, permeameter tests and flow meter tests (Zlotnik & Zurbuchen, 1998; Zlotnik et al., 2001). In contrast to some other hydraulic tests, the DFT does not require disposal of water, due to the recirculation in the subsurface. This is a significant advantage when testing contaminated aquifers, since the volume and associated cost of disposal of contaminated water can be significant.
The scale dependent aquifer anisotropy ratio, $a$, is a calculable parameter following the simple analytical methodology of Zlotnik & Ledder (1996), but in the improved analytical solutions since developed $a$ becomes a parameter required in the solution. It therefore requires prior testing (at the appropriate scale) or estimation, consequently introducing uncertainty into the solution (Roos, 2009). Previous applications of this method have assumed $a=1$ at the local scale, supporting the use of estimated values with the relatively weak dependence that radial hydraulic conductivity exhibits upon $a$ (Zlotnik & Zurbuchen, 1998; Zlotnik et al., 2001). The greatest problem with the dipole flow test, however, arises where the disturbed zone or well skin of the borehole provides a hydraulic short circuit between the chambers (Kabala, 1993). The DFT is likely to be more sensitive to the presence of such conductive well skins than other single-well hydraulic tests, since the DFT establishes a significant vertical flow field component (Zlotnik & Zurbuchen, 1998).

1.5.2 The Dipole Flow and Tracer Test (DFTT)

An advance to the DFT was presented by Sutton et al. (2000) involving the introduction of a tracer once the dipole flow field has been established. The tracer breakthrough curve obtained from this Dipole Flow and Tracer Test (DFTT) can be interpreted to yield dispersivity and the aquifer anisotropy ratio, from the tracer arrival front and peak, respectively (Sutton et al., 2000). The anisotropy ratio can then be used in the interpretation of the chamber drawdown data, to better resolve vertical and horizontal hydraulic conductivities using the analytical solution to the steady state drawdown (Sutton et al., 2000). With the DFTT, hydraulic short circuiting can be readily identified since an extra tracer peak is produced shortly after injection, whereas this phenomenon cannot be identified using only pressure heads, as in the DFT (Sutton et al., 2000). Furthermore, the tracer data is therefore believed to be relatively robust with respect to this skin effect, whilst the hydraulic data is more significantly affected (Sutton et al., 2000). More importantly, however, is the ability of the DFTT to prove (rather than infer) connection between the draw-up and draw-down evidenced in the chambers when tracer breakthrough occurs, evidencing mass transport. This is of particular significance for application of dipole tests in permeable fractured rocks.
1.5.3 The Dipole Flow and Reactive Tracer Test (DFRTT)

Recently, the Dipole Flow and Reactive Tracer Test (DFRTT) has been proposed and developmental research initiated (GPRG, 2009; Roos, 2009). Similar to the DFTT, the DFRTT involves the use of the dipole configuration to inject tracers, but also using reactive tracers in order to characterise biological and chemical hydrogeological properties of the aquifer material, using similar concepts to those applied in Partitioning Inter-well Tracer Tests (PITTs) (Jin et al., 1995).

1.6 Dipoles in fractured rocks

The interpretations and applications of the DFT, DFTT and DFRTT discussed so far, however, have only considered porous aquifer media. This research exercise, however, is focussed upon characterisation of fractured aquifers. Since the dipole flow field comprises a strong vertical flow component, as discussed previously, dipole based tests (i.e. DFT, DFTT, DFRTT) offer an opportunity to characterise vertical aspects of fracture networks in fractured aquifers, providing that the test “results” can be interpreted. A limited amount of work involving the use of dipole based tests in fractured aquifers has been conducted to date, which is now discussed here.

1.6.1 ADFT

A modification of the DFT is presented in Halihan & Zlotnik (2002), the Asymmetric Dipole Flow Test (ADFT), used to determine bulk conductive properties and to characterise the fracture network in a carbonate aquifer. The ADFT uses a single inflatable packer to divide the aquifer into two chambers (upper and lower) of variable length. Water is similarly pumped from one chamber to the other, causing draw-down and draw-up, recorded by pressure transducers in the two chambers. The test is repeated with the separating packer at different locations, altering the two chamber lengths. For each chamber, plots of specific drawdown versus chamber length are compared to two sets of “type curves”. The type curves are produced using a superposition of the Hantush solution, firstly for a set of curves representing different hydraulic conductivities and secondly for curves based upon a constant transmissivities. For the first set, drawdown is dependent upon chamber length and the scenario represents a relatively homogenous porous medium. For the second set, drawdown is independent of chamber length, representing a scenario where the transmissivity is controlled by a fracture which
remains within the chamber regardless of its length. The first set of curves allow inference of the hydraulic conductivity of a porous rock, whereas the second set allow the transmissivity of a fractured section to be inferred. Where the hydrogeological properties of the rock exhibit vertical heterogeneity (either in terms of un-fractured matrix hydraulic conductivity or presence of fractures), the data will not fit one individual type curve, but may be fit to a number of type curves allowing description of the heterogeneity in the borehole. Where the packer location passes an individual fracture, the change in chamber responses can thus be used to infer properties of the fracture. Similarly to other hydraulic techniques, the hydraulic aperture of the fracture may then be estimated.

The generation of the type curves is dependent (albeit weakly) upon the anisotropy ratio \( a \), similarly to DFT interpretations. The semi-quantitative ADFT interpretation approach assumes isotropic conditions, only considering anisotropy by comparing the isotropic type curves to those produced for two extreme anisotropy conditions.

When investigating fractured rocks, the concept of the anisotropy ratio requires careful consideration, since it is predominantly a porous media property. With respect to fractured impermeable rock, for instance, the anisotropy ratio may become either an obsolete term, or may be considered as a property describing the fracture network. In rock with a permeable matrix however, this term may be considered a matrix property, a property of the fracture network (as for the impermeable matrix) or else a bulk media property. The validity of the use of such a parameter relies upon its formal definition, whilst the ability to obtain a value true to the definition may become difficult.

The ability to identify individual fractures is enhanced if the transmissive fractures in the borehole are relatively widely spaced, as at the field site used by Halihan et al. (2002), since this provides greatest difference in the transmissivity changes in the chambers upon movement of the packer beyond the fracture location. Therefore, the value of the interpretation of this test is expected to be strongly affected by the scale of the test in relation to fracture spacing.

The asymmetry of the chamber lengths causes operational problems when testing near the top and bottom of a borehole, since the minimum pumping rates required for observable pressure changes in the longer chamber may be too great for the shorter chamber to sustain (Halihan et
al., 2005). These limitations are greatly magnified if the shorter section does not contain transmissive fractures. This may cause hydraulic fracturing when the shorter chamber is “over injected”, or complete drainage of the shorter chamber if it is “over extracted”, with both scenarios liable to damage equipment. Theoretical issues with the interpretation may also arise from over-extraction near to the surface which may conflict with the assumptions of using the Hantush solution for generating the type curves.

A modified version of the ADFT was conducted by Halihan et al. (2005), where a number of piezometers were installed in a 3D arrangement in the aquifer surrounding the dipole borehole to record head changes to give an insight into 3D aspects of the fracture network. This would naturally represent a significant increase in required drilling and therefore cost of the investigation, whilst the limitations of the 2D ADFT remain unresolved.

1.6.2 DFTT

Sandford et al. (2002) conducted a DFTT in a highly fractured silty-dolomite (with 4.8% porosity), using two conservative tracers. The dipole configuration comprised a series of permanent, vertically aligned piezometer installations, as opposed to the more commonly used portable down-hole packer based dipole probes. The test was interpreted by fitting a modelled breakthrough curve (BTC) to the BTC produced by the DFTT test. The modelled BTC considered a single fracture connecting the two chambers, modelled as 35 streamlines connecting the chambers in a circular arc of some radius. The modelling comprised a coupling of a 1D analytical solution for flow with an analytical solution for transport in parallel fractures, including matrix diffusion. The results for each streamline are summed to produce the modelled tracer breakthrough curve, with the fit of the modelled curve to the DFTT BTC achieved by iteratively altering the input parameters for the fractures in the model (including aperture, dispersivity and spacing).

Although the modelling approach was able to produce a similar BTC to that from the DFTT, the representativeness of the parameters of the best fit modelled curve are not discussed, nor is a sensitivity analysis of the model given, providing no evidence of the consideration of the solution uniqueness. The fracture spacing assumed in the analytical solution for fracture transport was unrepresentatively high in order to allow a single fracture connection to be
modelled. In light of the significant length (3m) and spacing (6m) of the dipole chambers in a highly fractured aquifer (5 fracture sets), it would seem unlikely that this assumption could allow accurate parameters to be reverse-modelled from the breakthrough curve, provided the model was reasonably sensitive to the parameters of interest.

The research by Sandford et al. (2002) does however represent a positive movement in the development of application of the DFTT to fractured media, albeit perhaps a somewhat ambitious attempt to interpret field results from a complex site, prior to establishing either a sound understanding of such an application of the DFTT or developing a robust interpretive approach.

This research project intends to take a logical step back from the work of Sandford et al. (2002) and to undertake an evaluation of the ability of DFTT to be interpreted to characterise the fracture network. Rather than attempting to interpret individual tests, this research aims to identify if unique breakthrough curves are generated by different fracture network configurations and fracture properties. This will allow conditions to be identified which allow or limit the successful interpretation of DFTTs in fractured rock aquifers. In contrast to previous studies, this research will consider a fractured aquifer media which exhibits a significant degree of matrix permeability, the Permo-Triassic sandstone, with a symmetrical “probe style” dipole configuration.
2. Aims and objectives of research

Aims
To investigate the effects of fractures upon Dipole Flow and Tracer Tests in fractured porous media. This represents the vital first stage in the assessment of the potential use of the DFTT as a tool to identify the presence and connectivity of fractures in the characterisation of contaminated groundwater sites.

Objectives
- To numerically model dipole flow and tracer tests in a dual porosity media characteristic of the UK Permo-Triassic sandstones.
- To develop an understanding of the effects of fracture presence upon the DFTT
- To assess the sensitivity of the DFTT to the location of fractures.
- To assess the sensitivity of the DFTT to the aperture of fractures.
- To develop methods of describing the shape of breakthrough curves in order to aid interpretation of DFTT responses.
- To develop an understanding of conditions which may allow or restrain the use of this technique in field applications.
3. Methods

3.1 Model background

HydroGeoSphere, a control-volume finite element numerical groundwater flow model, developed by the University of Waterloo and Université Laval, Canada (Therrien et al., 2008), will be utilised for this exercise. HydroGeoSphere was chosen since it is capable of coupling 3D flow and transport in porous media to flow and transport in discrete fractures. A finite difference approach is taken to solve mass transport.

3.2 Dipole Configuration and model implementation

3.2.1 Dipole Configuration

The configuration of the dipole probe modelled in this exercise are shown in table 3.2.1

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Notation</th>
<th>Chosen size (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chamber Length</td>
<td>2Δ</td>
<td>24</td>
</tr>
<tr>
<td>Packer length</td>
<td>2D</td>
<td>48</td>
</tr>
<tr>
<td>Probe radius</td>
<td>rₚ</td>
<td>8</td>
</tr>
<tr>
<td>Shoulder length</td>
<td>L</td>
<td>36</td>
</tr>
</tbody>
</table>

This dipole probe is specifically designed for identifying and testing the fracture network, therefore short chamber lengths are advantageous, similarly as for standard packer tests. The packer length for the dipole probe was chosen to represent reasonably long packers which for application of this technique could be chosen to ensure firstly a tight seal in the borehole and secondly to reduce the risk of flow into the borehole above and below the probe implemented section. The chosen radius is within the range of typical rock borehole diameters and is consistent with a ca. 6” borehole.

The injection and extraction chambers have been modelled as separate wells, sharing x and y co-ordinates thus located in vertical alignment. The injection well is located below the abstraction well, with positive and negative pumping rates (respectively) of 16.67 cm³ s⁻¹, or 1 L
The pumping rate affects the time to reach hydraulic steady state and the tracer breakthrough time, although the size of the dipole flow field generated by the probe is believed to be independent of the pumping rate (Zlotnik & Ledder, 1996). The time to reach hydraulic steady state is not a consideration in this modelling exercise, since Hydrogeosphere as default calculates the steady state solution for hydraulics before modelling transport (Therrien et al., 2008). The chosen pumping rate is reasonable for the size of the dipole probe and borehole, and could easily be achieved in the field. The breakthrough time arising from this pumping rate is sufficient to allow identification of the first arrival of the breakthrough curve to be identified, whilst breakthrough still occurs within reasonable time, approximately 15 minutes for an un-fractured scenario. Although a higher pumping rate could be utilised with this configuration, the use of a lower rate reduces the head gradients generated around the dipole chambers, which eases ensuring sufficient grid and temporal resolution to prevent significant numerical dispersion.

The impermeable packers have been represented as inactive elements in the model, which permit neither flow nor transport. Although HydroGeoSphere models wells as 1D line elements, the packers have been modelled with the aforementioned probe geometry, in order to impart the radial geometry into the models conceptualisation of the probe. The fractures are described as a series of planes surrounding the packers, since HGS cannot generate inactive elements through fractures. The redundant sections of borehole above the top packer (to the top of the domain) and below the bottom packer (to 1m above the bottom of the domain) have been modelled as fluid filled non-pumping wells. This represents a dipole probe located at some mid depth down a borehole, allowing interaction between the “stagnant” well water and the aquifer.

The modelled tracer has properties of Bromide, injected at a concentration of $1\times10^{-7}$ kg cm$^{-3}$, or 100 mg l$^{-1}$, with a free solution diffusion coefficient of $2.08\times10^{-5}$ cm$^{2}$ s$^{-1}$ (Lide, 1990). This concentration is sufficiently low that changes in fluid density and viscosity would be minimal and consequently hydraulic flow would not be affected (Schincariol & Schwartz, 1990).
3.2.2 Grid Discretisation and Time-stepping

After Zlotnik & Ledder (1996), the region of influence of dipole flow in an un-fractured porous medium is defined as the region within the stream surface containing 90% of the flow, located at a distance $10aL$ radially and $4L$ vertically (from dipole centres) where $a$ is the anisotropy ratio. The chosen dipole configuration, when modelled in a porous media, can therefore be expected to create a dipole flow field predominantly contained within 360 cm radially and 144 cm vertically from the dipole centre, given the shoulder length of 36 cm and an anisotropy ratio of 1. It is anticipated that the geometry and location of the modelled fractures or fracture networks will influence and control this predicted porous media region of influence in fractured scenarios.

To prevent significant boundary effects, a 20 x 20x 20 m domain has been chosen, significantly greater than the region of influence predicted. At the centre of this is a highly discretised central cube of 0.40 x 0.40 x 2.00 m ($x,y,z$ dimensions) with a node spacing of 4cm (level 2). Outside of this, node spacing is graded at a factor of 1.25 to a maximum of 8 cm to form a cube 4.80 x 4.80 x 5.60 m (level 1). Node spacing is then graded up to the domain boundaries, with a factor of 1.25 and a maximum node spacing of 2.00 m (level 0).

The level 2 grid zone enables adequate definition of the dipole probe configuration, whilst also helping to prevent numerical dispersion, since this zone will contain the strongest head and tracer concentration gradients.

The level 1 grid zone vertically contains the estimated 90% region of influence, although radially the 90% ROI is expected to extend beyond the level 1 grid discretisation. Due to the grading factor however, the node spacing at the boundary of the 90% ROI reaches only 30 cm. From Zlotnik & Ledder (1996), the stream surfaces containing 80% and 70% of the dipole flow are theoretically located at radial distances of $5aL$ and $3.5aL$ (180 and 126 cm) from the dipole centre respectively. It can therefore be seen that the 80% ROI is well contained radially within the level one zone.

The Peclet number $Pe$ (eq.2), a measure of the relative importance of advection versus dispersion, is recommended to be $Pe \leq 2$ in order to minimise artificial oscillation in the numerical solution (Zheng & Bennett, 2002).
With a longitudinal dispersivity of 20 cm, this therefore equates to node spacing less than 40 cm. Whilst this is not achieved throughout the domain, this node spacing is only exceeded in the outer “level 0” discretisation zone, beyond the predicted 90% region of influence discussed previously.

The Courant number \( Cr \) (eq. 3) is recommended to be \( \leq 1 \) for the implemented spatial and temporal discretisation, in order to prevent numerical dispersion (Anderson & Woessner, 1991).

\[
Cr = \frac{v \times \Delta t}{\Delta l}
\]  

(3)

The porous media is calculated to have a maximum (worst) value of \( Cr = 1 \) within the chambers, due to the high velocities found here and the longer time-steps toward the end of the simulation (table 3.2.2). Elsewhere in the domain, flow velocities are significantly lower and so this criterion is readily met, indeed, at the chamber-aquifer interface, \( Cr < 0.6 \). During the tracer injection (when numerical dispersion would have the most significant effects) the shorter time-stepping leads to a maximum Courant number of \( Cr = 0.2 \), well below the maximum.

<table>
<thead>
<tr>
<th>Start time (s)</th>
<th>Initial time-step (s)</th>
<th>Time-step multiplier (-)</th>
<th>Multiplier time-step limit (s)</th>
<th>End time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>1.05</td>
<td>5</td>
<td>925</td>
</tr>
<tr>
<td>925</td>
<td>5</td>
<td>0.95</td>
<td>1</td>
<td>1000</td>
</tr>
<tr>
<td>1000</td>
<td>1</td>
<td>1.05</td>
<td>10</td>
<td>1100</td>
</tr>
<tr>
<td>1100</td>
<td>10</td>
<td>1.05</td>
<td>50 or 10*</td>
<td>44000</td>
</tr>
</tbody>
</table>

Whilst the conformity to these requirements for an un-fractured porous media has been shown, it is expected that the presence of fractures will induce higher velocities, both in the porous media and within the fractures themselves. Due to the dependency of velocities upon the fracture location, it is not feasible to consider the Courant and Peclet numbers for such simulations in the discretisation of the grid and time-step optimisation.
In light of this, a conservative approach was taken during discretisation, with the resultant grid consequently at the limit of what the models flow solver matrix can handle (in terms of the number of nodes). Time-stepping was optimised with respect to the oscillation arising from this chosen grid and the resultant simulation run time; the output mass distributions, breakthrough curves and numerical tracer mass balances evidence the success of the chosen values.

### 3.2.3 Initial and Boundary Conditions

The initial head across the entire domain was set to 2000 cm. The HGS model then runs the problem until a steady state flow solution is reached. This steady state flow solution is subsequently used to solve the transport equations. To represent the dipole within a locally infinite aquifer, free flow and free mass outflow boundaries are appropriate, allowing velocity vectors and tracer mass to cross the boundary (i.e. defined boundaries for flow or transport would not be required). The hydraulic boundary conditions at such boundaries would be constant, due to the steady state nature of the problem, whilst for transport, the tracer concentrations at (and crossing) the boundary are transiently calculated during the simulation. However, at least two defined hydraulic boundaries are required for the mathematical basis of the model to function; therefore two vertical faces are defined as type one “Dirichlet” boundaries with respect to flow, with a head of 2000 cm specified for the duration of the simulation, with the remaining four faces “free” boundaries. Since the domain is large relative to the region of influence, significant head changes near to the boundaries of the domain are not expected, and therefore these specified head boundaries should not adversely affect the simulation.

For a simulation in an un-fractured porous media, head changes of less than 1 cm are found near the boundaries (which do not have specified head), in comparison to metres of pressure head changes near to the dipole chambers. Since only two faces have been defined as type 1 boundaries (the external y,z faces; planes x=0 and x=2000 cm) mass is still allowed to exit from the domain if it reaches the edge (for instance via fracture flow), whilst the size of the domain aims to limit this occurring.
3.3 Sandstone properties

The properties of the geologic medium have been chosen to be characteristic of the Permo-Triassic sandstone. The P-T sandstones are widely found in the UK (i.e. in the West Midlands, Cheshire, Nottinghamshire and Dumfriesshire) and represent important groundwater resources, both at present and likely for the future.

The values defining the properties of the sandstone used in this model, along with the sources of the values, are summarised in table 3.3i. A discussion of these chosen parameters now follows.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>notation</th>
<th>Value</th>
<th>units</th>
<th>definition</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Matrix hydraulic conductivity</td>
<td>K</td>
<td>9×10⁻⁴</td>
<td>cm s⁻¹</td>
<td></td>
<td>a</td>
</tr>
<tr>
<td>Anisotropy ratio</td>
<td>a</td>
<td>1</td>
<td>-</td>
<td>(\sqrt{K_L² + K_T²})</td>
<td>b</td>
</tr>
<tr>
<td>Matrix porosity</td>
<td>n</td>
<td>0.25</td>
<td>-</td>
<td>Effective porosity</td>
<td>c</td>
</tr>
<tr>
<td>Matrix longitudinal dispersivity</td>
<td>(\alpha_L)</td>
<td>20</td>
<td>cm</td>
<td></td>
<td>d</td>
</tr>
<tr>
<td>Matrix transverse dispersivity</td>
<td>(\alpha_T)</td>
<td>2</td>
<td>cm</td>
<td></td>
<td>e</td>
</tr>
<tr>
<td>Matrix transverse vertical dispersivity</td>
<td>(\alpha_{VT})</td>
<td>0.2</td>
<td>cm</td>
<td></td>
<td>e</td>
</tr>
<tr>
<td>Matrix Tortuosity</td>
<td>T</td>
<td>0.5</td>
<td>-</td>
<td>Straight line/path length</td>
<td>b</td>
</tr>
<tr>
<td>Bromide free diffusion coefficient</td>
<td>D*</td>
<td>2.08×10⁻⁵</td>
<td>cm² s⁻¹</td>
<td></td>
<td>f</td>
</tr>
<tr>
<td>Fracture aperture</td>
<td>e</td>
<td>0.05</td>
<td>cm</td>
<td>Aperture between parallel plates.</td>
<td>b</td>
</tr>
<tr>
<td>Fracture longitudinal dispersivity</td>
<td>(\alpha_{Lf})</td>
<td>50</td>
<td>cm</td>
<td></td>
<td>g</td>
</tr>
<tr>
<td>Fracture transverse dispersivity</td>
<td>(\alpha_{Tf})</td>
<td>50</td>
<td>cm</td>
<td></td>
<td>g</td>
</tr>
</tbody>
</table>

Sources:
- c. Allen et al., 1997; Scott and Barker, 2006.
- e. Based upon the commonly used 100:10:1 ratio for \(\alpha_L:\alpha_T:\alpha_{TV}\).

The matrix hydraulic conductivity is based upon the value of 8.4×10⁻⁴ cm s⁻¹ used in Mayer et al. (2001) for a P-T sandstone near Wolverhampton, which lies within the range of typical hydraulic conductivities of 1.16×10⁻⁴ to 1.16×10⁻² cm s⁻¹ for PT sandstones (Tellam and Barker,
2006). Whilst the P-T sandstones often exhibit anisotropy, with horizontal hydraulic conductivities greater than vertical, anisotropy ratios of 1 (i.e. isotropy) is also common (Tellam and Barker 2006). Whilst some anisotropy in the grain structure may arise from the depositional orientation of non-spherical grains, many Permo-Triassic sandstones are composed of lithified Aeolian deposits. These tend to comprise fairly well-rounded grains, whilst the lithifying carbonate cement likely reduces any anisotropy. Additionally, published anisotropy values may not be appropriate for use at this small scale, since the anisotropy ratio has been found to increase with observation scale, due to bedding and layering (Allen et al., 1997). Furthermore, literature values likely represent the “bulk anisotropy”; that is, the anisotropy ratio of bulk conductivities vertically and horizontally, without separating the contribution of fractures from the matrix. The use of such values here to define purely the matrix would therefore be erroneous. These lines all support the assumption of isotropy taken for this exercise.

The effective porosity is taken between the median and mean values published by Allen et al. (1997) and Scott and Barker (2006) who presented ranges of 0.15 to 0.30 with a mean of 0.24 and median of 0.26.

Values for matrix dispersivities in the Permo-Triassic sandstones based upon rigorous field-scale observations are not widely available, with the exception of data cited in Gelhar et al. (1992), shown below in table 3.3ii.

<table>
<thead>
<tr>
<th>Primary Source</th>
<th>Location</th>
<th>Media</th>
<th>Hydraulic conductivity (cm s(^{-1}))</th>
<th>Scale of test (m)</th>
<th>Longitudinal Dispersivity (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oakes &amp; Edworthy</td>
<td>Clipstone, Nottinghamshire, UK</td>
<td>Sandstone (Sherwood Triassic Sst)</td>
<td>2.4 ×10(^{-3}) to 1.4 ×10(^{-2})</td>
<td>6</td>
<td>16, 38</td>
</tr>
<tr>
<td>(1977)</td>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td>31</td>
</tr>
</tbody>
</table>

These values were classified as being of the medium (II) level of reliability by Gelhar et al. (1992), whilst the scale of these tests are similar to the expected size of the dipole flow field (the streamline lying on the predicted 80% ROI has a length of approximately 6 m). Consequently, values in the region of those Oakes & Edworthy presented in Gelhar et al. (1992) are considered to be appropriate for this exercise. Whilst Mayer et al. (2001) use a value of 1 m for matrix dispersivity, the scale of the dipole flow test is substantially smaller than the plume.
scale considered by Mayer et al.; consequently the use of a value less than 1 m in this exercise is justified and considered consistent with Mayer et al. (2001). Providing further support for using a dispersivity smaller than 1 m is the analysis of sandstone dispersivity data presented in Schulze-Makuch (2005); trendline fit parameters from which estimate a dispersivity of 5 cm from a 6 m flow path length.

The chosen value of tortuosity lies within the range of values used, derived and mentioned by numerous authors for PT sandstones; Cai et al. (2006) calculate a theoretical value of 0.2 using $T=n^{4/3}$ (after Millington, 1959). Cai et al. (2007) derive a value of 0.3 from Br’ breakthrough curves, whilst Tellam and Barker (2006) cite values >0.5 and >0.66.

Fracture apertures are within the summary ranges presented by Allen et al. (1998) for bedding plane fractures (10 µm to 10 cm) and jointing fractures (10 µm to 1 mm). A range of apertures are used for one family of simulations, whilst 500 µm is used where aperture is not the variable under study.

The fractures are modelled in this exercise to extend beyond the edge of the domain in order to avoid introducing the additional complexity of fracture terminations. Based upon the summary range of trace lengths reported in Tellam and Barker (2006), bedding plane fractures greater than 20 m in length are considered wholly representative of Permo-Triassic sandstones.

Taylor dispersion theory can be used to calculate dispersivity in parallel plates exhibiting poiseuille flow (Fisher et al., 1979; Brenner & Edwards, 1993) and consequently has seen use in previous modelling exercises to calculate fracture dispersivities (Cai et al., 2006; Cai et al., 2007a). The value for Taylor dispersion is calculated using the solute diffusion coefficient, fracture aperture and the mean fluid velocity in the fracture. This last parameter proves problematic for this exercise however, since the velocity field is non-uniform and will vary for each fracture network configuration. Taylor dispersion has therefore not been used; instead a similar approach to that taken by Cai et al. (2007b) is followed. This is based upon the assumption that dispersivities in porous and fractured media are similar, following trends observed by Gelhar et al. (1992) and Schulze-Mukach (2005). Since flow within the fractures is likely to occur at a larger scale than within the matrix, a dispersivity value greater than those
used for the matrix has been chosen in order for fracture dispersivity to be scaled to the domain size. Additionally, the chosen values are consistent with values reported in Gelhar et al. (1992) for fractured media of a similar domain size.

3.4 Rationale of Proposed Scenarios

Since this investigation represents a novel and unique exercise, both as research of the DFTT and modelling of fractured aquifers, a prescriptive scenario matrix would have been limited the research value of this project. Consequently, a dynamic and responsive approach was taken, allowing the results from each simulation to direct subsequent scenarios. The conceptual framework guiding this approach, along with its underlying rationale, is presented here.

An un-fractured porous media scenario is the first simulation since an un-fractured porous media is fundamentally an end-member scenario for a fractured porous matrix rock- where no fractures are present. This also provides a simple scenario from which to develop our understanding of flow and mass transport in the dipole flow field and the resultant breakthrough curve, prior to applying this to the interpretation of fractured scenarios.

The first family of fracture scenarios consider a single horizontal fracture located at different intervals across the domain. The fractures have an aperture of 500 µm. This family of scenarios is chosen in order to assess the effect of a single fracture upon the tracer breakthrough curve, to understand how responses are affected by the fracture location and to identify the “region of fracture influence” (ROFI). This is the region within which the presence of a fracture will influence the DFTT response.

The second family of fracture scenarios focus upon the effect of the aperture of a single horizontal fracture. Apertures of fractures are altered for fractures at key locations, based upon the results of the first family of scenarios. These will include the elevations exhibiting the greatest sensitivity to fracture presence and the elevation defining the limit of the ROFI.
3.5 Analysis Techniques

This research has primarily focused upon analysis of the tracer breakthrough curves arising from the concentration of tracer measured at the point of abstraction, in the abstraction chamber. A number of common breakthrough curve metrics have been chosen to use in this analysis, which are now discussed. An example breakthrough curve is shown in figure 3.5 with the different metrics identified.

3.5.1 First arrival

The first arrival of the tracer front is the time at which the tracer concentration starts to increase above the background baseline. In order to maintain consistency in the analysis and for this modelling exercise to be representative of physical experiments, the time at which the tracer concentration exceeds the method detection limit has been chosen as the first arrival time in this exercise. Using a Dionex Ion-Chromatograph, a detection limit of 0.4ppm for Bromide is possible (A. Fairburn, Pers.Comm 2009) and is subsequently taken as the MDL throughout this exercise. The first arrival is produced by the mass which has taken the “fastest” flow path (Käss, 1998); this may not necessarily be the shortest flow-path, or that with the highest velocity however.

3.5.2 Peak arrival

The peak concentration and arrival time of the peak concentration are two further measures which are easily identified as the apsis of the breakthrough curve. The peak arrival represents the dominant arrival of mass, although a “characteristic” velocity cannot easily be interpreted from this due to the complexity of flow and flow paths in this problem.

3.5.3 Mean front arrival

The mean front arrival is the time at which the tracer breakthrough (the “rising limb” of the BTC) reaches half the concentration of the peak. This method, in combination with the peak concentration time, yields information describing the tracer arrival front, particularly useful when the first arrival metric cannot be easily distinguished or when the derived first arrival is not meaningful. Such situations may arise where background tracer concentrations are non-zero and fluctuating, producing high “background noise”; when comparing breakthrough of
different tracers with different method detection limits; or where the detection limit is high relative to the peak concentration.

### 3.5.4 Centre of mass arrival

The arrival of the centre of mass, or “mean arrival time” is defined as the time when half the recovered tracer mass reaches the observation point. Where flow rates are constant, this is equivalent to the time on the breakthrough curve where the areas under the curve either side of the point are equal. Due to the common “lognormal” tailing of breakthrough curves, the arrival of centre of mass is usually found after peak arrival. The centre of mass arrival time is calculated using the method of “temporal moments”. Unlike the methods for the previously discussed metrics, the temporal moment approach uses all of the breakthrough data; consequently this metric is sensitive to the overall shape of the breakthrough curve and in particular can provide useful information on tailing of the breakthrough curve.

The centre of mass arrival, $t^*$ is calculated by dividing the first order temporal moment by the “zeroth” order temporal moment (eq 4):

$$ t^* = \frac{m_1}{m_0} \quad (4) $$

With the temporal moments defined in (5):

$$ m_k = \int_{t=0}^{t=\infty} t^k C(x, t) dt \quad (5) $$

Where $k$ is the order of the moment and $C(x, t)$ the tracer concentration at position $x$ at time $t$ (Ptak & Schmid, 1995). Since the breakthrough curve comprises discrete data points, the integration of the breakthrough curve is undertaken using an approximation based upon the inertia technique (6) (Shook, 2005):

$$ m_k = \sum_{i=1}^{N} C_i t_i^k \Delta t_i \quad (6) $$

Most breakthrough curves exhibit some degree of tailing, where baseline concentrations are not reached within the observation period. Due to the slow decline in tracer concentration in the tail (often approximated by exponential decline) the tail can contain a considerable amount of tracer mass. Consequently, the data should be extrapolated beyond the end of the
modelled/observed data (at time $t_b$). Unless this is undertaken, the mass contained within the tail is not considered by the temporal moments calculation and the arrival time of the centre of mass is underestimated. Late-time observed/modelled data should be fit with an exponential function (if appropriate), defining the tail concentrations by (7):

$$C(t) = be^{-\alpha t}$$

and consequently used to extrapolate beyond time $t_b$. Symbolic integration yields equations 8 and 9 for the zeroth and first temporal moments of the tail portion of the breakthrough curve:

$$m_{0, \text{inf}} = \frac{b}{\alpha} e^{-\alpha t_b}$$

$$m_{1, \text{inf}} = \frac{b}{\alpha^2} e^{-\alpha t_b} (1 + \alpha t_b)$$

The temporal moments for the model data and tail data can then be summed and used in equation (4) to calculate the mean arrival time, $t^*$.

The use of equations 8 & 9 result in integration of the extrapolated data (based on the exponential fit) to infinite time. Such a method, whilst mathematically rigorous, is considered not to be realistic of physical experiments, since even if observation could be conducted until infinite time, the tracer concentrations will undoubtedly decline below the method detection limit. To overcome these issues and to present a sound, consistent and practical approach, the late time data is extrapolated to the time at which the tracer method detection limit is reached ($t_{mdl}$) and subsequently used to calculate the mean arrival time, using:

$$t^* = \frac{m_{1, \text{mod}} + m_{1, \text{inf}} - m_{1, \text{mdl}}}{m_{0, \text{mod}} + m_{0, \text{inf}} - m_{0, \text{mdl}}}$$

with $m_{k, \text{mdl}}$ calculated using equations 8 and 9, using the same exponential curve fitting parameters ($\alpha$ and $b$), but substituting $t_{mdl}$ for $t_b$, calculated using (11):

$$t_{mdl} = \frac{\ln C_{mdl}}{\frac{b}{-\alpha}}$$

$C_{mdl}$ is the method detection limit of 0.4 ppm.
Figure 3.5. Example breakthrough curve demonstrating the different metrics and the tail extrapolation used to derive the temporal moments. A full discussion of the metrics and their derivation is provided in the main body of text.
4. Results and Discussion

4.1. Un-fractured Porous Media

An un-fractured porous media is fundamentally an end-member scenario for a fractured porous matrix rock - where no fractures are present. It is therefore essential to understand the DFTT response from such a scenario and the underlying processes (both hydraulic and mass transport phenomena) responsible for the particular DFTT breakthrough response. Furthermore, a comprehensive understanding of the processes occurring in this simple baseline scenario is highly important for the later interpretation of DFTT responses from fractured scenarios, aiding the phenomenological interpretation of any differences in the responses arising from the presence of fractures.

4.1.1. Hydraulics of the Dipole Flow Field

The pressure heads from the dipole flow test, even for a simple un-fractured scenario, are relatively complex, comprising spatially varying pressure gradients, directionally and in intensity. Figure 4.1.1a shows a vertical 2D slice through the whole domain, showing the steady state head distribution surrounding the dipole probe, which is located centrally. The upper half of the domain exhibits reduced head pressures and the lower half pressure head increases; this is consistent with the relative locations of the abstraction and injection chambers respectively.

![Figure 4.1.1a & b. Un-fractured Scenario. a) Vertical 2D slice through the centre of the domain showing head contours and stream traces. b) Close-up view (340 cm wide) of a, with the grid mesh (2D) overlaid. Note the strong draw-up and draw-down surrounding the lower and upper chambers, respectively.](image)
Note that the 20 m head contour lies horizontally across the domain, located centrally and serving to separate the upper and lower portions of the domain. The hydraulic influence of the dipole flow field can be seen to extend to the edges of the domain, although the pressure head differences are less than 1cm at the boundaries. The 1cm head contour extends less than 2 m radially from the centre of the borehole and are symmetrical either side of the probe, in the Y plane as well as the X plane shown in this slice. Vertically, however, the pressure head differences propagate further, reaching the top of the domain above the probe, and extending downwards towards the bottom of the domain. This arises due to the presence of the fluid filled well, which extends beyond the domain above the probe and below the probe to 1m from the domain boundary. The outer stream-traces in figure 4.1.1a extend widely across the domain, although the velocity of such flow-paths is very small, due to the small hydraulic gradient.

Figure 4.1.1b shows the head distribution and consequent stream-traces (again for a 2D slice) in the vicinity of the dipole probe. The three packers, isolating the injection and abstraction chambers in the borehole, are indicated by the blank rectangles. The head distribution and flow-paths exhibit a strong symmetry, both horizontally (about the central vertical axis) and vertically (about the central horizontal axis). The pressure head differences in the two chambers exceed ±4 m from the initial head of 20 m, highlighting the relative insignificance of the sub centimetre head difference at the domain boundaries.

Since the pressure head in the injection chamber is greater than the head across the whole domain, flow consequently occurs in all directions away from the chamber, not only towards the abstraction chamber. The stream-traces in figure 4.1.1b shows this divergence of flow away from the injection chamber; with flow-paths originating from the upper half of the injection chamber diverging upwards towards the abstraction chamber, and those originating from the lower half of the injection chamber initially diverging downwards. Since the pressure decrease around the abstraction chamber increases the hydraulic gradient towards this chamber, the lower stream-traces can also be seen to curve outwards and upwards. Note that all the stream-traces are oriented vertically when they reach the midpoint between the upper and lower portions of the domain, since they cross perpendicular to the horizontal 20 m head contour previously identified (figures 4.1.1a&amp;b). Upon entering the upper portion of the domain, the flow-paths curve inwards (and downwards) towards the abstraction chamber.
The flow-paths closest to the central packer exhibit the greatest flow velocities in the dipole flow field, indicated by the closest spacing of the pressure head contours, in addition to being the shortest flow-paths between the two chambers. The average hydraulic gradient along any flow-path between the two chambers is dependent only upon its length, since the pressure differential between the two chambers is constant. As the aquifer properties are homogeneous and isotropic in this scenario, the average velocity along any flow-path is proportional only to this gradient. Thus the flow path length defines both the velocity and the travel distance; the travel time along any flow-path is consequently proportional to the square of its length. The travel-times along the short inner flow-paths are therefore significantly faster than those towards the outside.

4.1.2. Mass Transport Within The Dipole Flow Field

Figure 4.1.2i shows a series of 2D slices as “snapshots” of the propagation of the tracer mass from the injection chamber under the steady state hydraulic conditions discussed above. Tracer concentration is indicated by the shading colour, contoured logarithmically from the injection concentration (dark red, $1\times10^{-7}$ Kg cm$^{-3}$) to below the method detection limit (dark blue, $<4\times10^{-11}$ Kg cm$^{-3}$) (units as in the model).

![Image](image_url)

**Figure 4.1.2ia to f.** (Continued overleaf). Mass distribution snapshots for the un-fractured media. Head contours and stream-traces are shown in the background. Time frames are 90, 600, 1500, 9000, 18000 and 44000 seconds.
The first snapshot at $T=90\,\text{s}$ shows the tracer mass migrating almost uniformly radially from the injection chamber, although beginning to show preferential vertical transport close to the central packer (where the highest velocity flow-paths lie). This is further evidenced in the next snapshot ($T=600\,\text{s}$), where the mass distribution is noticeably elongated towards the abstraction chamber. By the next snapshot ($T=1500\,\text{s}$), the tracer mass front has reached the abstraction chamber, whilst the tracer mass distribution continues to expand radially.

The subsequent snapshots show the continued expansion of the tracer mass and the decrease in concentrations propagating from the injection chamber after cessation of the tracer input. Analogously to the start of tracer injection, concentrations do not immediately reduce to zero within the injection chamber, instead gradually reduce as the tracer-free water mixes within the chamber. The development of a “halo” like distribution, due to this injection
of tracer-free water, can be seen from \( T = 9000 \) s. This tracer-free water migrates along the fastest flow-paths towards the abstraction chamber, whilst the slower flow-paths further out from the injection chamber contains the remaining tracer mass. The halo of mass continues migrating along these slower flow-paths, entering the middle region of the abstraction chamber, whilst tracer-free water from the faster flow-paths enters the bottom region of the abstraction chamber. It should be noted however that the whilst the tracer distribution is seen here in 2D as a halo, this is actually three-dimensional and should therefore be envisaged as a “ball” of tracer mass developing into a spheroidal (hollow) form.

In the snapshots at \( T = 9000 \) and \( 18000 \) s, the development of a spike of tracer migrating vertically downward below the bottom packer, due to tracer entering into and migrating through the water filled redundant portion of the borehole. It is likely that the length of the bottom packer controls the extent to which mass will migrate into the borehole below the dipole probe. This implication of packer length should therefore be considered in the design of dipole probes, in order to prevent this redundant portion of the borehole behaving as a significant sink of tracer mass during a DFTT.

In the snapshot for \( T = 9000 \) s, a small amount of mass can be seen to be anomalously migrating vertically upwards above the abstraction chamber. This occurs due to how the model handles the nodes at the interface between the “active” porous media and the “inactive” elements defining the packers, from which the mass then diffuses into the porous media and returns advectively to the abstraction chamber. This error only exists in the transport phase of the simulation, since the pressure heads and flow velocities do not evidence flow here. The amount of mass affected is minor and is believed to have an insignificant effect upon the breakthrough curves, although presumably reduces the magnitude of the peak and increases the early tail concentrations as this mass advects to the abstraction chamber. Since HydroGeoSphere is the most appropriate groundwater model for simulating the DFTT in a fractured porous media, this minor limitation of the model must at present be accepted.

Figures 4.1.2ii-a & b show vertical and horizontal (intersecting the middle of the injection chamber) cross sections of the pressure heads and mass distribution relative to the whole domain at \( T = 44000 \) s. It can be seen that the mass is well contained within the domain, both
vertically and radially. Figure 4.1.2ii-b shows the radial symmetry of both the pressure heads and mass distribution, confirming that the boundary conditions do not influence the dipole flow field in the region of the probe. Some slight angularity can be seen in the mass distribution, likely as a consequence of the elongated grid blocks due to the graded discretisation of the grid. This effect is not expected to cause any appreciable differences into the breakthrough curves. Due to model and computational limitations, extension of the zone of finest discretisation to reduce the elongation of grid blocks was not possible.

**Figure 4.1.2iia & b.** a) Vertical slice through whole domain showing the mass distribution at T=44000s. b) Horizontal slice through the whole domain at elevation of z=964, the middle of the injection chamber. Note the well constrained mass distribution in both aspects.

### 4.1.3. Breakthrough Curve

The un-fractured scenario breakthrough curve (Figure 4.1.3) can be seen to exhibit the common lognormal shape of tracer breakthrough curves, with a sharp arrival front and slower decline after the peak concentration has arrived.

The sharp arrival front of the breakthrough curve represents the arrival of the mass transported along the fastest flow-paths close to the central packer. The tracer concentration of the water abstracted from the chamber reaches the method detection limit at 970 s. The tracer concentrations at the abstraction well increase as the volumetric flow of tracer-containing water reaching the abstraction chamber increases, synonymous with an increase in the number of flow-paths yielding tracer bearing water at the abstraction well. Additionally, initial dilution of the tracer in the injection chamber is significant, with the tracer concentration
increasing with the duration of tracer input. Thirdly, dispersive processes cause “spreading” of the leading edge of tracer mass migrating through the porous media, leading to an increasing concentration upon the arrival of mass from each flow-path. It is important to note that this latter effect is not the primary control on the arrival front, since the larger scale dispersive effect arising from the varying length and velocity flow-paths of the dipole flow dominate. Thus, unlike standard tracer test breakthrough curves, the arrival front is not indicative simply of the dispersive properties of the aquifer media.

The first arrival time occurs at 971 s and represents the mass which has migrated along the fastest flow-paths, consequently is an indicator of the travel time along the fastest flow-path, closest to the central packer. The velocity along this flow-path is controlled by the hydraulic gradient provided by the head differential between the two chambers.

The mean front arrival occurs at a time of 2343 s (where concentrations are half that at the peak), whilst the peak concentration occurs at 4850 s. The peak concentration occurs when the tracer mass flux at the abstraction point is at a maximum, since the rate of abstraction remains

![Breakthrough curve for the Dipole Flow and Tracer Test in the un-fractured simulation.](image-url)
constant. This maximum tracer flux consists of the combined individual fluxes from the $n$ fastest flow-paths (the $n$ inner-most flow-paths). The maximum flux occurs when the decrease in flux along the fastest (i.e. a subset) of these $n$ flow-paths, due to the cessation of tracer input, exceeds the increase in total tracer mass flux provided by the contribution from the $n+1$th flow-path. The time of the decrease in flux along the fastest flow-paths is therefore dependent upon the duration of injection and the travel time along these fastest flow-paths. Since the duration of injection is kept constant at 1000 s for all scenarios, it is the velocity of the flow-paths which can be expected to determine the time of the peak concentration.

The BTC peak for this un-fractured scenario has an absolute concentration of $2.48 \times 10^{-9}$ Kg cm$^{-3}$, or 2.48% of the injection concentration. Since the mass flux of each individual flow-path is dependent upon their velocity, the total tracer mass flux at the abstraction point, and therefore the peak concentration, is also dependent upon the velocity of the flow-paths.

The subsequent slow decline in concentration after the peak represents the decreasing tracer flux from the faster flow-paths whilst slower flow paths, further out from the injection chamber, continue to contribute tracer mass. It is the slowest flow-paths which provide the mass causing the long tailing of the breakthrough curve. The arrival of the centre of mass (the first normalized temporal moment) $T^*$, is calculated to occur at 25100 s, considerably after the other metrics, due to the mass contained in the tail.

The tracer mass recovered at the abstraction chamber is calculated to be 52.53% of the injected tracer mass (until concentrations fall below the method detection limit). This suggests that a significant portion of the mass still remains within the domain by the time the method detection limit is reached in the abstracted water. This mass is contained at low concentrations in the very slowest flow-paths, which although do return to the abstraction well, are at concentrations below the method detection limit.
4.2. Fracture Location.
This section presents, interprets and discusses the results obtained for the family of scenarios in which a single 500 µm aperture horizontal fracture plane is present, located at different elevations.

4.2.1. Results
4.2.1.1. Breakthrough curves
The DFTT breakthrough curves obtained from a selection of scenarios with the fracture located at different elevations are shown in figure 4.2.1.1, in addition to the un-fractured porous media breakthrough curve (as previously discussed) for comparison.

![Breakthrough curves for fractures at varying location. All fractures have an aperture of 500µm. Z value refers to the elevation of the horizontal fracture plane.](image)

It can be seen that the presence of the fractures tends to delay the initial breakthrough, delay the peak arrival and reduce the peak concentration, whilst the tail exhibits a slower decline in concentration. The fractures modify the hydraulics of the dipole flow field and contribute to flow and mass transport, since with an aperture of 500 µm, they have a hydraulic conductivity significantly greater than the porous matrix (by four orders of magnitude).
Two fractured breakthrough curves shown in figure 4.2.1.1 are indistinguishable from the un-fractured scenario however; one where the fracture is located across the middle of the central packer (z=1000 cm) and secondly where the fracture is at some distance below the dipole chamber (z=856 cm).

The breakthrough curve from the scenario with the fracture located at z=940 (below the injection chamber) shows the least difference in shape to the un-fractured curve, although has lower peak and tail concentrations.

The remaining breakthrough curves, which are from the scenarios with fractures located between the outer ends of the packers, exhibit significant differences to the un-fractured scenarios. The degree of difference between these breakthrough curves and that of the un-fractured scenario varies, dependent upon the location of the fracture. The differences are least significant for the fracture located between the central packer and injection chamber (z=988 cm) but increase further away from the central packer.

The curves exhibiting the greatest difference are those with fractures located at elevations of z = 1048 & 952 cm, corresponding to the upper end of the abstraction chamber and lower end of the injection chamber (furthest from the central packer), respectively. The first arrival can be seen to be considerably delayed, whilst the peak arrives at 17200 s, considerably later than for the un-fractured scenario (4850s). The peak concentrations for these two scenarios are low at 5.7×10⁻⁷ Kg cm⁻³, only marginally higher than the tail concentrations at the end of the simulations (ca 4×10⁻⁷ Kg cm⁻³), which decrease only very slowly. Consequently, less confidence can be held in the calculated centre of mass arrival time, due to the greater significance of the mass contained in the extrapolated portion of the curve.

From the breakthrough curves in figure 4.2.1.1 pairs of scenarios can readily be identified, which, whilst different to the un-fractured scenario response, are near-identical to each other. These pairs are for scenarios where the fractures are located equal, but opposite, distances from the central packer- for instance the scenarios producing the most altered breakthrough curves, with fractures at the bottom of the injection and top of the abstraction chambers (z=1048 and 952, respectively). This suggests that it is the distance of the fracture from the
centre of the dipole, rather than the distance from the point of tracer injection, which predominantly controls the form of the breakthrough curves.

4.2.1.2. Breakthrough Curve Metrics

The various metrics (as defined previously in the methodology) for all breakthrough curves from this family of scenarios are presented in figure 4.2.1.2. These metrics have been normalised to the respective values from the un-fractured scenario, thereby allowing simple comparison of the effect of fracture location upon each metric relative to the un-fractured scenario. Where the normalised metric = 1, no difference between the un-fractured and fractured metric is found, >1 the fracture metric is greater, <1 the fracture metric is smaller. The location of the fracture is described by the distance from the middle of the central packer normalised to the shoulder length, L (36 cm). The centre of the central packer (z=1000) is therefore 0, whilst the middle of the injection and abstraction chambers are located at -1L and +1L (Z=1036, 1024 cm), respectively. The inset diagram explains the derivation of these dimensions and the dipole configuration in such terms.

From figure 4.2.1.2, it can be seen that the presence of fractures tends to increase the temporal metrics (The first, mean front, peak and centre of mass arrival times), whilst the peak concentrations are reduced. The benefit of using these metrics to compare the curves can now be seen, since they allow quantification of differences in the shapes of breakthrough curves. The subsequent visualisation in figure 4.2.1.2 provides a comprehensive description of multiple breakthrough curves in a manner which allows any trends associated with fracture location to be identified.

When a fracture is located across the centre of the middle packer, the metrics are all equal to the un-fractured response, consistent with the breakthrough curves as discussed above.

Moving outward from the middle of the central packer (either up or down) the differences to the un-fractured response increase. Interestingly however, the differences do not increase greatly between fractures located at -\(\frac{1}{2}L\) and -\(\frac{3}{2}L\), increasing sharply beyond this. The differences consist of an increase in the temporal metrics (i.e. are delayed) which exhibit a maximum difference at the end of the chambers furthest from the central packer (±1\(\frac{1}{2}\)L). The
peak concentrations decrease with respect to the un-fractured scenario, also exhibiting the greatest difference at $\pm 1\frac{1}{3}L$. The location of such maximum differences corresponds to the breakthrough curves exhibiting the greatest difference to the un-fractured breakthrough curve, as discussed previously.

Figure 4.2.1.2. Normalised Breakthrough Curve Metrics. See main text for description of the derivation of the normalised values. Note the vertical symmetry about the dipole centre.
The peak concentration is the metric exhibiting the greatest difference to the un-fractured scenario response, with normalised concentrations of 0.23 (more than four times lower). Of the temporal metrics, the first and peak arrival times exhibit the greatest delay, with maximum normalised values of 3.8 and 3.6 respectively.

Moving out further from the mid-chamber location, the difference to the un-fractured scenario response decreases sharply for all metrics, with only relatively slight differences at \(-1\frac{1}{3}L\). Interestingly, the normalised centre of mass arrival time decreases marginally below zero at \(-1\frac{1}{3}L\), such that the absolute value of the metric is slightly less than the value for the un-fractured scenario. All metrics approach unity with increasing distance below the central packer and are indistinguishable from the un-fractured scenario response at \(-4L\).

Symmetry about the dipole centre can clearly be seen in figure 4.2.1.2, with similar trends in normalised metrics for fractures located above and below the dipole centre. This is consistent with the observation made earlier for the pairs of breakthrough curves in figure 4.2.1.1. Slight differences in response do exist between the positive and negative normalised fracture locations however, with a greater delay in all temporal metrics and a lower peak concentration for a fracture at \(+L\) compared to \(-L\) (figure 4.2.1.2).

### 4.2.2. Interpretation and discussion

#### 4.2.2.1. General explanation of the influence of fractures.

Similarly to the un-fractured scenario in figure 4.1.1, the inner flow paths are those with the fastest travel times, therefore controlling the first arrival time and strongly influencing the peak arrival time. The observed delay in these metrics can therefore be explained by considering the effects of the fractures upon the hydraulics of these flow-paths. Where fractures are in the injection half of the dipole flow field (at some \(-ve\) \(L\)), the fractures allow flow away from the dipole centre, reducing the pressure head increase or “draw-up” in the injection chamber. This is evidenced by the asymmetry seen in figure 4.2.2.1 below. Where fractures are located in the abstraction half of the dipole flow field (at some \(+ve\) \(L\)), the fracture contributes to flow toward the abstraction chamber, similarly reducing the pressure head decrease or “draw-down” occurring in this chamber.
Either scenario results in a reduced pressure differential between the two chambers, consequently decreasing the vertical component of the hydraulic gradient, averaged along any flow-path, between the chambers. The mass transport along the inner flow-paths is therefore reduced, delaying not only the first arrival, but also the time at which the reduced tracer flux (due to cessation of tracer injection) reaches the abstraction chamber, which exerts a strong control upon the peak arrival time.

Since the flow rates along the inner flow-paths are reduced, the flow along the outer flow-paths must increase in order to maintain hydraulic mass balance. Consequently a greater proportion of tracer mass migrates via these outer flow-paths which, due to their length and lower average velocity, increase the tailing in fractured scenarios. This is evidenced visually in the breakthrough curves and quantitatively by the calculated centre of mass arrival metric.

The peak concentration is defined as the maximum mass flux at the abstraction point, which is dominated by the mass flux from the inner flow paths, since these have the greatest flow velocity and therefore flux. Since the flow velocities along these flow paths are reduced in the presence of fractures, their mass flux is similarly reduced, despite similar tracer concentrations to the un-fractured scenario. The reduced combined tracer flux from these flow-paths is consequently the predominant cause in the reduction in the peak concentration, supported by the similarity between the proportional decrease in peak concentration and increase in the first and peak arrival times.
4.2.2.2. **Non-influential fractures**

At the middle of the central packer, the pressure head contours of the dipole flow field are horizontal and parallel across the whole domain; when a fracture is located in this plane the flow is consequently perpendicular to the fracture across the whole plane. Since there is no horizontal component to the pressure gradient, transport of fluid or tracer mass along the fracture does not occur. A fracture located here would therefore theoretically be “invisible”, from both the tracer breakthrough curve and from the hydraulic (pressure head) signal in the two chambers, despite being located within the dipole flow field. This is shown for a 2D slice in figure 4.2.2.2i, where the head contours and stream-traces are indistinguishable from those for the un-fractured porous media scenario in figure 4.1.1b.

![Figure 4.2.2.2i. Head distribution for a fracture located at the elevation of the middle of the central packer.](image)

Note the fracture overlies the 2000cm head contour, whilst stream-traces cross the fracture perpendicularly.

The second scenario arises where the fracture is located beyond the “region of fracture influence” (ROFI) of the dipole probe, with the portion of aquifer tested comprising predominantly un-fractured porous matrix. The pressure head distributions for this scenario are shown in figure 4.2.2.2ii-a&b, in which some small changes to the pressure heads in the outer region of the dipole flow field can be seen. Closer to the dipole probe, the strong hydraulic gradients which exert a dominant control upon the mass transport and tracer breakthrough are not significantly affected by the fracture. This can be seen from the contour lines in figure 4.2.2.2ii-c, where the mass distribution also shows that even after 44000s only a small amount of mass has spread along the fracture below the probe. Since the slowest flow-paths are found immediately below the probe, the radial fracture spreading presumably allows the mass to reach slightly faster flow-paths, although these would likely still only contribute to the portion of tail far below the method detection limit.
4.2.2.3. Influence of fracture location

**Below probe**

The near indistinguishable difference between the response of the un-fractured scenario and that for a fracture located at \(-\frac{1}{3}L (z=940 \text{ cm})\) can be explained by the influence this fracture exerts upon the dipole flow field and its contribution to tracer mass transport. The fracture does not intersect either chamber and so the head differential between the chambers is 822.5 cm, reduced only by 1.5\% in comparison to the un-fractured scenario.

Whilst this results in slightly lower velocities and fluxes along these inner flow-paths, they remain otherwise relatively unaffected hydraulically by the presence of the fracture. The outer regions of the flow field are primarily affected since the fracture is located below the probe, towards the outside of the flow field. Since the hydraulics of the inner flow paths control the first, front and peak arrival times of the breakthrough curve, these metrics are only affected by the minor changes in velocity and flux arising due to the head change.
The peak concentration is more sensitive to changes in the outer flow-paths, since it is composed of the innermost $n$ flow-paths, a larger subset of flow-paths than those which control the first and peak arrivals. In addition to the reduced head differential, the tracer mass transport towards and along the fracture decreases the combined flux of the $n$ flow-paths comprising the peak.

The tail exhibits lower concentrations due to the proportion of mass which migrates along the fracture and takes slower flow-paths to the abstraction chamber. Provided that these flow-paths do reach the abstraction chamber at some time, a longer tailing should be evidenced. This should theoretically increase the centre of mass arrival time, although since this is calculated for the curve extrapolated until the mdl is reached, the mass contained in the portion of the tail after the method detection limit is reached will not be reflected in this metric. This explains the (apparent) shorter centre of mass arrival time for this scenario.

*Between chambers*

The difference between the response of the un-fractured scenario and that for a fracture located at $-\frac{1}{3}L$ ($z=988$ cm) is now considered. Similarly to the fracture located below the probe, the presence of the fracture results in only a small change to the pressure differential between the chambers. This contributes to the delay in the first and peak arrival times and the reduced peak concentration.

Since the fracture lies within the inner regions of the dipole flow field, it contributes more significantly to tracer mass transport than for fractures located below the probe. As the head contours in the matrix are almost parallel to the fracture, flow through the fracture is predominantly perpendicular to the fracture plane, although a small radial flow component exists. Due to this small radial hydraulic gradient and dispersion within the fracture, some mass does migrate radially however. This serves to provide a “short-cut” for mass to enter matrix flow-paths further out in the dipole flow field, initially delaying the peak arrival (by effectively increasing the $n$ flow-paths contributing flux). After the peak arrival however, this radial spreading causes the “wider” peak and serves to increase the tailing of the curve, delaying the arrival of the centre of mass.
**Intersecting the chambers**

Consideration is now given to the flow and mass transport in those scenarios where fractures intersect the chambers. As has been identified previously, the location of this intersection exerts a great influence over the resultant breakthrough curve; fractures at the outer end of the chambers has a more significant impact than at the inner end of the chambers, where a relatively similar response to a fracture located above the chamber has been found.

When a chamber is intersected by a fracture, the magnitude of the draw-down or draw-up is reduced relative to the un-fractured scenario (i.e. ±14 cm compared to ±418 cm). This occurs since a lower gradient is required to transmit flow out of the chamber due to the significantly higher hydraulic conductivity of the fracture relative to the matrix. The reduction in draw-down/-up results in a pressure differential between the chambers of approximately 440 cm, significantly lower than the un-fractured scenario (835 cm). The pressure differential is relatively insensitive to the location of the fracture intersection, differentials of 437 and 441 cm for fractures intersecting the top and bottom (respectively) of the injection chamber were found.

**Top of injection chamber**

Where the fracture intersects the top of the injection chamber, flow is induced from the mid-chamber injection point towards the fracture intersection, then radially through the fracture. The head pressure in the fracture is greater than in the matrix and flow consequently diverges from the fracture, converging towards the abstraction chamber in response to the draw-down influence. Since the radial gradient induced in the fracture is predominantly dissipated by flow into the matrix, the fracture transmits little water out of the domain.

Since the fracture is located at the top of the chamber, all flow-paths between the chambers must cross the fracture plane. The fastest flow-paths are those which remain closest to the central packer, whilst the slower flow-paths diverge further along the fracture.

The head distribution around the abstraction chamber remains similar to the un-fractured scenario, although draw-down propagates further downwards due to the reduced draw-up
from the injection chamber. This can be seen by the location of the 20m head contour below the middle of the central packer (figure 4.2.2.3ia).

Compared to the un-fractured scenario, the travel time along the fastest flow paths is increased due to the lower hydraulic gradient. This delays the first and peak arrival, whilst the reduced velocity decreases the tracer mass flux which influences peak concentrations. The mass transported to the abstraction chamber via flow-paths diverging from the radial fracture flow initially delay the peak arrival time, by effectively increasing the $n$ flow-paths contributing tracer mass flux at the peak. After the peak arrival time however, this continued radial spreading of mass further along the fracture causes mass to enter increasingly slower flow-paths. This results in the slower decline after the peak and the increased tailing, thereby increasing the centre of mass arrival metric.

**Bottom of Injection**

When the fracture is located at the bottom of the injection chamber, drawdown from the abstraction chamber propagates further towards the injection well, since the draw-up induced from the fracture is located further from the abstraction chamber. Flow from the injection point of the chamber is consequently influenced by the drawdown, with the fastest flow-paths consequently not entering or crossing the fracture, but migrating up the chamber and lying close to the central packer. The majority of flow-paths enter the fracture however, and display

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**Figure 4.2.2.3ia & b.**a) Head and b) Mass distributions for a fracture located at the top of the injection chamber, $z=976$. Note the strong asymmetry in the head distributions and effect upon mass distribution. $T=1500$ s
similar divergence out of the fracture and re-convergence towards the abstraction chamber (figure 4.2.2.3ii-a & b).

The greater distance between the fracture and the abstraction chamber decreases the gradient along the flow-paths which diverge from the fracture, since the head differential remains the same, whilst their length also increases. Similarly, the fastest flow-paths also experience reduced gradients between the injection point and abstraction chamber. Consequently, the first and peak arrival times are increased whilst the reduced tracer mass flux reduces peak concentrations. Since the gradient between the fracture and abstraction well is weaker, spreading along the fracture occurs to a greater extent (figure 4.2.2.3ii b), thus amplifying the widening of the peak and longer tailing.

4.2.2.4. Symmetry of results

This section considers the similarity in DFTT responses arising from the pairs of scenarios where fractures are located the same distance above or below the central packer. This was identified in section 4.2.1, identified from the pairs of similar breakthrough curves seen in figure 4.2.1.1 and the vertical symmetry of figure 4.1.2.2.
The scenarios which produce responses most different to the un-fractured response, where the fractures are located at the outer ends of the two chambers, are considered here.

The hydraulics of the two scenarios can be seen to exhibit a rotational symmetry, but with flow in the opposite direction (figure 4.2.2.4i-a&b). This is expected, since the magnitude of the injection and abstraction rates are the same, whilst the configuration of the probe and fractures are essentially symmetrical. Since the radial gradient induced in the fractures is predominantly dissipated by flow into or from the matrix, the fractures transmit little water into or out of the domain. Consequently, nearly all flow-paths join the two chambers and the probe may be considered as hydraulically isolated.

The only asymmetry in the configuration is in the “redundant” portion of the borehole, which is considered to extend to the top of the domain above the probe, whilst below, is terminated 1 m above the base of the domain. As discussed previously, this causes only slight asymmetry in the outer pressure head distribution and likely exerts no significant effect on mass transport. The hydraulics of the pair of scenarios can therefore reasonably be considered as identical, simply with flow in the opposite direction. This is analogous to “reversing” the pumping rates of the chambers, so that the abstraction chamber injects, and injection abstracts.
The flow-paths in the scenario pairs are consequently the same length, and indeed shape, although flow is in the opposite direction. Since the pressure head differential between the two chambers remains the same, the average gradients along each flow-path remain the same and consequently the travel-time along each flow-path is identical. The change in gradient along the flow-paths is however altered, with one scenario being the “reversed negative” of the other. This is illustrated by a plot of the head change along the same flow-path from the two scenarios- a rotational symmetry about the labelled point can be seen which represents the “reversed negative” concept.

The snapshots of mass distribution appear very different, arising due to the reversed negative gradients, and hence velocity, in addition to shape of the flow-paths. The mass is, however, migrating along the same flow-paths, which consequently will arrive at the abstraction chamber at the same time. The mass distribution in figure 4.2.2.4ii-a can be seen to be closer to the abstraction chamber than in figure 4.2.2.4ii-b, due to the higher gradients around the injection chamber. Migration along the remainder of the flow-path will be slower however, due to the low gradients around the abstraction chamber, whilst in 4.2.2.4ii-b, velocities increase nearer the abstraction chamber.

This hydraulic “symmetry” and connection of flow-paths suggests that the breakthrough curves should be identical for such scenario pairs, however slight differences are seen. These subtle differences are likely to arise due to numerical dispersion as a consequence of the different
mass transport phenomena relative to the time-stepping of the simulation, which increases towards the end of the simulation. When the fracture intersects the injection chamber, the dominant fracture mass transport occurs at early time, whilst the highest mass flux in the matrix occurs at later time when mass is nearing the abstraction chamber. Conversely, fracture mass transport occurs nearer the end of the simulation and highest matrix mass flux at early time when the fracture intersects the abstraction chamber. The resultant differences in numerical dispersion is believed to result in the delay of the first, peak and centre of mass arrivals and reduced peak concentration evidenced for the abstraction chamber. That the differences are greater for the scenario pairs with fractures closer to the central packer (figure 4.2.1.1) may be explained by higher velocities arising from greater hydraulic gradients within these dipole flow fields.

4.3. Fracture Aperture.

This section focuses upon the effect of the fracture aperture upon the DFTT response. The investigation is focussed on two principal objectives; to identify if the trends associated with the location of the fracture (presented in section 4.2) hold for fractures of different apertures; and secondly to investigate if the response of the DFTT is sensitive to the aperture of the fracture. The simulated matrix of scenarios therefore includes both the fracture aperture and location as variables in order to address both these objectives. Since the “symmetry” between locations above and below the central packer is expected to occur irrespective of the fracture size, the subsequent investigation focuses upon location below the central packer, i.e. in the vicinity of the injection chamber.

4.3.1. Results

4.3.1.1. Breakthrough curves for varying location

5mm Aperture
The breakthrough curves for three locations, z=1000, 952 and 940 cm, are shown in Figure 4.3.1.1i. It can be seen that at z=1000 cm, the breakthrough curve is very similar to the un-fractured scenario, with only a slight reduction in peak concentration.
At $z=940$ cm, below the bottom of the injection chamber, the 5mm fracture produces a breakthrough curve which exhibits a lower peak concentration and lower concentrations after the peak than the un-fractured concentration. The first and peak arrivals are not significantly different to those for the un-fractured scenario. The breakthrough curve for the 5 mm fracture located at the bottom of the injection chamber ($z=952$) exhibits a significantly delayed first and peak arrival, with a significantly increased tailing after the peak. The duration of the simulated period was increased to 20 hours for this fracture location in anticipation of such an increased tailing, based upon the results for the 500 $\mu$m fractures presented earlier. The magnitude of the differences to the un-fractured curve are greater than produced by the 500 $\mu$m fractures presented earlier.

200 $\mu$m Aperture

A greater number of locations were simulated with 200 $\mu$m fractures, since such an aperture lies more centrally within the typical range of apertures for the PT sandstones than 5mm fractures. Figure 4.3.1.1ii shows the resultant curves produced, which appear to be comparatively less affected by the 200 $\mu$m fractures than either the 500 $\mu$m or 5 mm fractures.
The fracture closest to the central packer, at Z=988 cm, produces a breakthrough curve with slightly reduced peak concentration and an increase in tailing. It is this latter difference which distinguishes this fracture location from z=940, below the injection chamber, where the breakthrough curve has a similarly reduced peak but also lower tail concentrations.

With a fracture at Z=976, the peak concentration is reduced, but the first and peak arrivals appear similar to the un-fractured curve, whilst also exhibiting a similar degree of tailing. For a fracture located at 964 cm however, the breakthrough curve shows a greater peak reduction, an increase in tailing and a slight delay in the peak arrivals. The greatest difference to the un-fractured breakthrough curve is produced by a fracture at z=952, the bottom of the injection chamber, with a peak concentration less than half that of the un-fractured scenario, delayed first and peak arrivals and greater tailing.

100 µm Aperture
The set of curves for the 100 µm fractures (Figure 4.3.1.1iii) exhibit important differences to those for the larger fractures, not simply a reduction in the magnitude of differences to the un-fractured scenario. The scenario with a fracture located at z=976 cm, the top of the injection
chamber, produces a breakthrough curve with a higher peak concentration and faster peak arrival time than the un-fractured scenario. However, for a fracture at z=988 cm, closer to the central packer, the peak concentration is significantly reduced. For a fracture located at z=940 cm, below the injection chamber, the curve is essentially indistinguishable to that of the un-fractured scenario. The fractures at Z=964 and 952 cm produce curves with delayed peak arrival times and reduced peak concentrations, whilst the curves appear to exhibit greater tailing. The latter curve can be seen to exhibit a strong similarity to its “opposite” scenario: a fracture located at z=1036, the middle of the abstraction chamber.

50 µm aperture
The location previously identified as most sensitive to the presence of the 5mm, 500, 200 and 100 µm fractures, z=976 cm, yields a breakthrough curve for a 50 µm fracture revealing only slightly reduced peak concentrations relative to the un-fractured scenario (Figure 4.3.1.iv). At z=976, where the 100 µm fracture resulted in a faster peak, little difference can be seen to the un-fractured scenario.
Figure 4.3.1.1ii. Breakthrough curves for 100µm fractures at varying locations

Figure 4.3.1.1iv. Breakthrough curves for 50µm fractures at varying locations
4.3.1.2. BTC Metrics

A selection of the metrics describing the breakthrough curves for all scenarios are displayed in figure 4.3.1.2i, using the same normalisation approach as previously. From this, the influence that fracture aperture has upon the magnitude of the differences can be seen, with larger fractures generally resulting in greater differences in the breakthrough curve metrics.

At $-1\frac{2}{3}L$ the temporal metrics exhibit little difference to those of the un-fractured scenario, regardless of fracture aperture, although the magnitude of the slight peak concentration differences correlate to fracture aperture.

The responses of 100 and 200 µm fractures exhibit less sensitivity to location than the larger fractures, with the responses at $-1\frac{1}{3}L$ comparatively less different to those at $-1L$.

The normalised metrics for a 200 µm fracture located at $-\frac{3}{4}L$ are closer to 1 than when the fracture is located either nearer to or further from the central packer. This is particularly noticeable for the peak concentrations. The magnitude of response is also lower here for the 100 µm fracture, whilst the normalised first and peak arrivals are less than 1: the first and peak arrivals occur sooner than for the un-fractured scenario. The breakthrough curves in figure 4.3.1.2ii also evidence these effects of the fracture aperture at this location.

The bottom of the injection chamber, $-1\frac{1}{2}L$, is the most sensitive to the presence of fractures, exhibiting the greatest difference in the metrics for fractures of all apertures. The difference in peak concentration between the 500 and 5mm fracture here is minimal however, whilst the response of the 50µm fracture is not significantly different to that of the un-fractured response. These observations can also be observed in the breakthrough curves presented in figure 4.3.1.2iii.
Figure 4.3.2.1i. Normalised breakthrough curve metrics for varying apertures at different locations.
Figure 4.3.1.2ii. Breakthrough curves for fracture located at the top of the injection chamber, varying aperture.

Figure 4.3.1.2iii. Breakthrough curves for fracture located at the top of the injection chamber, varying aperture.
4.3.2. Interpretation and Discussion

4.3.2.1. Non-influential fractures
Similarly to the 500 µm fracture, a 5 mm fracture located across the middle of the central packer exerts no significant influence upon the DFTT response due to the perpendicular orientation of flow to the fracture plane. The slight reduction in peak concentration may arise from the increased diffusion along the fracture, whilst with increasing aperture the entering flow presumably has a slightly greater horizontal component, thus increasing the influence of the fracture. This effect likely remains insignificant however, whilst background gradients within the fracture would likely have a greater influence in practical applications.

Below the bottom of the injection chamber, the influence of fractures upon the DFTT response is generally insignificant since they are not in direct connection with the chamber and therefore do not significantly alter the pressure differential, as flow through the matrix to these fractures must still occur. Since the magnitude of the difference in peak concentration increases with aperture size, it may be proposed that the distance below the chamber that the region of influence extends may be scaled to some function of the aperture size, although since it remains a short distance is likely a non-linear relationship.

4.3.2.2. Influence of Aperture
The magnitude of the difference between the response of a fractured scenario and the un-fractured response is positively correlated, in general, with the fracture aperture. Consideration is first given to the hydraulics of fracture flow within the DFTT, and the implications of aperture size on the DFTT response are then developed from this for the scenarios where fractures are located at the bottom of the injection chamber.

The hydraulic conductivity of a fracture is proportional to the square of its aperture (eq 12):

\[
K_f = \frac{\rho g a^2}{12 \mu}
\]

(12)

Where \( K_f \) is the hydraulic conductivity of the fracture.
By substituting equation 12 for $K_m$ (matrix hydraulic conductivity) and the fracture aperture and width for $A$ (the area through which flow occurs) into equation 13 (Darcy’s equation for flow) the Cubic Law is arrived at (eq. 14):

$$Q_m = K_m A l$$  \hspace{1cm} (13)  

$$Q_f = \frac{e_0 w_0 g w}{12\mu}$$  \hspace{1cm} (14)

It can thus be seen that the flow through a fracture is proportional to the hydraulic gradient and the cube of the aperture. As the flow rate in the DFTT is constant, it is the hydraulic gradient (and therefore the induced draw-up/-down) which varies as a consequence of the fracture aperture. Since, however, the DFTT is conducted in a fractured rock with a porous matrix, this also contributes to flow, dependent upon the hydraulic gradient into the matrix from the chamber (13). The greater the fracture aperture, the lower the gradient and the lower the flow into the matrix from the chamber, whilst the sum of the flow into the matrix and fracture flow remains equal the pumping rate. The head pressure surrounding the injection chamber is also influenced by the draw-down from the abstraction chamber, which therefore affects hydraulic gradient.

A decrease in the aperture therefore leads to a significant decrease in the contribution of the fracture to flow. The trends in the temporal metrics and peak concentrations for the 500, 200, 100 and 50 $\mu$m fractures shown in figure 4.3.1.1ii demonstrate the influence that this has upon the response of the DFTT at the bottom of the injection chamber, which is explained here now.

The pressure differential in the matrix between the fracture and the abstraction chamber exerts a control on the hydraulic gradient along any flow-path, whilst the curvature of the flowpath also affects the gradient due to the length. As has been shown above, the smaller the fracture aperture, the less the fracture contributes to flow and the greater the draw-up in the injection chamber. This results in an increase in the head differential between the fracture and abstraction chamber, and therefore the gradient along flowpaths through the matrix between the two. Furthermore, the increase in draw-up in the chamber results in greater flow between the chambers directly through the matrix, without entering the fracture. This can be seen in figure 4.3.2.2 from comparison of the head distributions (a & b) and mass distribution snapshots (c & d) for 500 and 200 $\mu$m fractures located at the bottom of the injection chamber. With the smaller aperture fracture, less mass has migrated along the fracture, and more from
the chamber into the matrix, with the higher gradients resulting in the mass reaching the abstraction chamber sooner.

![Figure 4.3.2a, b, c, d](image1.png)

**Figure 4.3.2a, b, c, d.** Top: Head distributions for a) 500 µm and b) 200 µm fractures; Bottom: Mass distributions for c) 500 µm and d) 200 µm fractures located at the bottom of the injection chamber. T=1500s

The increased gradient along flow-paths between the fracture and abstraction chamber, in addition to the increased contribution directly through the matrix decreases the travel-time to the abstraction chamber. This results in faster first and peak arrivals and higher peak concentrations than for larger fractures, whilst the decrease in mass transport along the fracture into the slower outer flow-paths reduces the tailing. It should be noted, however, that the curvature of the flow-paths through the matrix are greater with a smaller aperture fracture, due to the higher radial pressure gradient from the chamber. The associated increase in length
of the flowpaths is presumably insignificant in comparison to the increased head differential, despite the squared relationship between path length and travel time.

4.3.2.3. Aperture and sensitivity to fracture location.

The magnitude of the difference between the un-fractured and fractured scenarios appears to be less sensitive to fracture location for smaller aperture fractures than those of larger apertures, as evidenced for 500, 200 and 100 µm fractures in figure 4.3.1.2i.

As discussed in the previous section, the proportion of flow directly from chamber to chamber through the matrix increases with decreasing aperture of the fracture, since it contributes less to flow from the injection chamber. Consequently, with decreasing aperture, the contribution of flow-paths which enter then subsequently diverge from the fracture, in terms of both volumetric flow and tracer mass flux, decreases. The breakthrough curve is therefore increasingly dominated by flow-paths which are independent of the fracture flow, thus the distance between the fracture and abstraction chamber exerts a less significant effect upon the breakthrough curves than for larger aperture fractures. This is well illustrated by the mass snapshots in figure 4.3.2.3 a & b for a 100 µm fracture located at the bottom and middle of the injection chamber.

![Figure 4.3.2.3 a & b](image)

**Figure 4.3.2.3 a & b.** Mass distributions for 100µm fractures at a) z=952 and b)z=964, T=90s. View width is 170 cm.
The front of the tracer mass migrating along the fastest flow-paths can be seen to be in the same location, despite the difference in fracture location. The first and peak arrival times which are strongly controlled by the fastest flow-paths will therefore be similar, showing less sensitivity to location. The location of the fracture continues to exert a control over the migration of mass along flow-paths further out, consequently the peak concentration and tailing of the breakthrough curves remains relatively more sensitive to the location of the fracture. This is evidenced by the more peaked shape of the centre of mass arrival and peak concentration metrics for the 200 μm fracture in figure 4.3.1.2i.

4.3.2.4. The influence of fractures at $-\frac{3}{3}L$.

Based upon the same reasoning provided for the 500 μm fractures, it is logical that the normalised metrics for a 200μm fracture at the top of the injection chamber are closer to 1 than when located at the bottom of the injection chamber, due to the increased travel-time along flowpaths between the fracture and abstraction chamber. It is perhaps surprising, however, that when the fracture is located above the top of the injection chamber the resultant normalised metrics indicate a greater difference than for a fracture intersecting the top of the chamber.

This can be explained by the different extent to which the two fractures contribute hydraulically. When the fracture is located above the top of the injection chamber, a small radial flow component is induced within the fracture, due to the sub-perpendicular orientation of the matrix pressure heads. This leads to “spreading” of mass along the fracture, slowing the migration of the tracer front and decreasing the front concentration. Since the fracture does not intersect the chamber, the head differential between the chambers is not significantly different to that for the un-fractured scenario.

When the fracture intersects the chamber, flow into the fracture is induced radially. Flowpaths subsequently diverge from the fracture and re-converge towards the abstraction chamber as a result of the hydraulic gradient developed both by draw-down from the abstraction chamber and the draw-up providing the gradient inducing fracture flow. The flow-paths between the chambers are therefore composed of sections of fracture and matrix flow, with the travel time
a function of the distance and velocity along both sections. The higher velocity of fracture-flow could therefore comparatively reduce the overall travel-time of a flow-path if fracture flow more than compensated for the reduced head differential through the matrix. The flowpaths which diverge from the fracture beyond the central packer could therefore contribute to the observed relatively less-reduced peak concentration, since they would contribute tracer mass flux to the abstraction chamber sooner due to the faster fracture flow.

The first and peak arrivals are controlled to a greater extent by the innermost fastest flow-path, which lies between the two chambers close to the central packer. This should theoretically cross the fracture near-perpendicularly and would therefore not benefit from faster fracture-flow, but instead be slowed by the reduced head differential through the matrix. Due to how the fracture-chamber intersection is conceptualised in the model however, this fastest flow-path incorporates flow through the fracture from the centre of the 1D well to the outer edge of the packer. Although only a short distance (the radius of the packer) the high velocities in the fracture here may therefore erroneously reduce the travel time along this fastest flow-path, causing the relatively less delayed first and peak arrival metrics.

The earlier first and peak arrivals for a 100 µm fracture locate at the top of the injection chamber than those of the un-fractured scenario can be explained by similar reasoning; for a small aperture fracture, the reduction in gradient between the fracture and abstraction chamber is small, and the fracture increases the transport velocity of the tracer sufficiently to reduce the overall travel-time along flowpaths between the chambers.

There must presumably be some critical aperture at which the contribution of the fracture velocity exceeds the delay arising from the reduced head differential through the matrix.

4.3.2.5. Aperture sensitivity limits.

The area through which flow occurs into the matrix from the chamber is equal to the chamber length, $2\Delta$, multiplied by the chamber perimeter. For the fracture, the area is proportional to the fracture width, $w$, which at the interface between the fracture and chamber is equal to the perimeter of the chamber. Flow both into the fracture and matrix are therefore dependent
upon the radius of the borehole, whilst matrix flow is also dependent upon the chamber length $2\Delta$. Thus the chamber length will affect the relative proportions of fracture and matrix flow, whilst the chamber radius has no effect. Based upon this, and equations 13 and 14, equation 15 can be derived, assuming that the local hydraulic gradient $i$ from the chamber into both the fracture and matrix are equivalent:

$$\frac{Q_f}{Q_m} = \frac{(\varepsilon^3 \rho g / 12 \mu)}{K_m 2 \Delta}$$

(15)

Since the fluid properties may be considered constant, the contribution of the fracture to flow from the chamber is proportional to the cube of the aperture and the inverse of the hydraulic conductivity and chamber length. Using the modelled sandstone matrix hydraulic conductivity and dipole dimensions, plus fluid properties for 10 °C, a 50 µm fracture could contribute less than 4% of the matrix flow, whilst a 100 µm fracture could contribute 29% of the matrix flow. This therefore explains the small response seen for the 50 µm fracture, despite it still having a hydraulic conductivity more than two orders of magnitude greater than the matrix (eq 12), it likely contributes little to flow from the chamber. Presumably some minimum contribution to flow, greater than 4% and possibly as much as 30%, is required for the fracture to significantly affect the breakthrough curve. By reducing the chamber length of the modelled probe, the sensitivity limit could presumably be reduced, perhaps allowing identification of slightly smaller fractures.

Consider a fracture of some aperture that is able to transmit flow at a rate equal to the pumping rate, under a hydraulic gradient sufficiently small for flow into the matrix from the chamber to be negligible. A fracture of larger aperture could therefore not contribute more to flow from the chamber, although the flow velocity in the fracture would be decreased. By rearranging equations 13 & 14, equation 16 is derived, describing the “representative” hydraulic gradient $i_r$, where the injection rate $Q_i$ is equal to the sum of the flow into the matrix $Q_m$ and fracture $Q_f$,

$$i_r = \frac{Q_i}{\left(\varepsilon^3 \rho g w / 12 \mu\right) A K_m}$$

(16)

By substituting $i$ in (13) with $i_r$ from (15), the matrix flow contribution can be estimated for a given aperture fracture. Using the dipole chamber dimensions to calculate $A$, standard fluid properties and the matrix conductivity of $9 \times 10^{-4}$ cm s$^{-1}$, it is found that a 500 µm fracture would
transmit 97% of the flow from the chamber. This is likely the explanation of the limited difference in the response of the 5mm fracture compared to the 500 µm fracture, since the 5mm fracture already transmits the majority of the injected flow-rate from the chamber. 500 µm therefore likely approximates the near maximum aperture that can be resolved from this combination of matrix properties and dipole configuration. Note that by either decreasing the chamber length, or by increasing the pumping rate, the consequent increase in gradient would presumably allow sensitivity at greater aperture, provided that tracer breakthrough still occurred.

4.4. Breakthrough Curve Descriptor

The “ultimate” breakthrough curve descriptor would allow breakthrough curve data to be interpreted to infer characteristics of the fracture network, such as fracture hydraulic aperture or connectivity.

Since this project represents the first stage in the research of the application of the DFTT in fractured porous rocks, derivation of such an “ultimate” descriptor is unattainable from the families of scenarios modelled here, however a single value which could be used to distinguish between the curves produced in this modelling exercise was sought.

The resultant value or “Shape Factor” is shown in figure 4.4.

This shape factor was calculated using equation 17:

\[
SF = \frac{T_3^* \times C_{pk} \times T_{front}}{T_{finst} \times C_{inj} \times T_{pk} \times T_3^*}
\]  

(17)

Where \( T_3^* \) is the third temporal moment, a measure of the skewness of the breakthrough curve (Govinadaraju & Das, 2007), is calculated from the breakthrough curve data using equation 18:

\[
T_3^* = \frac{m_{3mod} + m_{3infin} - m_{3tmdl}}{m_{0mod} + m_{0infin} - m_{0tmdl}}
\]  

(18)

based upon equation 10 given previously. \( m_{3mod} \) is calculated using equation 6 and the extrapolated values \( m_{3tmdl} \) and \( m_{3infin} \) with equation 19, substituting \( t_{mdl} \) and \( t_{infin} \) for \( t_x \) respectively:
These measures were chosen since they describe different aspects defining the shape of the breakthrough curve and ultimately produce the most unique shape factor. The constant of $1 \times 10^{17}$ was introduced to yield values within a sensible range, since the third temporal moment has very large values due to the log normal shape of the breakthrough curves (a highly skewed distribution).

$$m_{3t} = \frac{b}{a^3} e^{-at} (a^3 t_x^3 + 3a^2 t_x^2 + 6at_x + 6) \tag{19}$$

**Figure 4.4.** The “Shape Factor”, as derived by equation 17. The normalised fracture location approach is as used previously.
It can be seen that the value of the Shape Factor for a fracture is dependent upon the location of the fracture, due to the strong influence that fracture location played in the response of the DFTT. It is also sensitive to the aperture of fractures, between 500 µm identified previously as the maximum for this dipole configuration, and the 50 µm fracture, despite the general lack of significant response in the individual breakthrough curve metrics. The un-fractured curve has a Shape Factor of 415, whilst it ranges from 5 for the largest fracture at the most sensitive location, to 450 for the 100 µm fracture at the unique location where it results in earlier breakthrough. The most sensitive location, at the bottom of the injection chamber, offers the best range in values, with the 50, 100, 200 and 500 µm fractures yielding distinct shape factors which are all smaller than the un-fractured response.
5. Conclusions and Operational Guidance

5.1. Conclusions

The dipole flow and tracer test has been shown to be sensitive to both the location and aperture of single horizontal fractures. The presence of fractures tends to delay the arrival and peak of breakthrough curves, reduce the peak concentrations and increase the tailing, with the magnitude of these effects correlated to the aperture of the fracture. The intersection of the chamber leads to a reduction in draw-down or draw-up, controlled by the conductivity of the fracture the size of the chamber and the pumping rate used.

The location of fractures has been found to exert a strong control upon the magnitude of the response, with a “Region of Fracture Influence” extending between the outer ends of the chambers. The greatest response is found where the fracture intersects the outer end of the chamber, either the top of the abstraction chamber, or bottom of the injection.

Due to the symmetry of the dipole flow field, a fracture plane located at the elevation of the middle of the central packer is theoretically invisible to the DFTT, both from the draw-up/-down monitored in the chambers and from the breakthrough curve produced from the DFTT. Fractures located the same distance either side of the central packer produce identical breakthrough curves, again due to the symmetry of the dipole flow field. The location of the fracture relative to the packer can be identified by the draw-down or draw-up monitored in the chambers compared to the initial or background pressure head; the fractured side will exhibit a lesser change in pressure from the initial head than the un-fractured side.

Under certain conditions, a fracture located at the inner end of the chamber may produce a breakthrough curve exhibiting no sign of fracture presence, although the chamber head pressures evidence fracture presence.

Even in the presence of a large, highly conductive horizontal fracture intersecting the chamber a DFTT breakthrough can still be achieved, due to the strong vertical hydraulic gradients imposed by the test.
The sensitivity of the DFTT to fracture aperture is controlled not only by the fracture aperture and the matrix conductivity, but also by the pumping rate and the length of the chambers. With the configuration used in this model, the Shape Factor indicated a reasonable sensitivity to fractures with apertures between 50 and 500 µm; it is thought that increasing the flow rate and reducing the chamber size would allow this range to increased.

5.2 Operational guidance

Whilst the application of the DFTT would require further research to develop our understanding of more complex scenarios, the following protocol is proposed based upon the knowledge gained from this project.

- Due to the sensitivity of the DFTT to fracture location, Multiple (3 or 4) DFTT tests should be conducted, moving the probe slightly each time (i.e. a distance of Δ, half the chamber length).

- The chamber head pressure should be monitored, since these allow determination of fracture location, relative to the central packer and the individual chamber.

- The breakthrough curves of the DFTT should be processed to produce metrics describing the shape of the curve, such as those used to define the “Shape Factor”.

- The change in the magnitude of the shape factor, in combination with the draw-up and draw-down measured in chambers, can be used to indicate the location of the fracture. The magnitude of the shape factor could then be used to estimate the aperture from a chart such as that presented in section 4.4, presuming the probe configuration and aquifer matrix are compatible.

- Due to the DFTT aperture sensitivity dependence upon the dipole flow-rate and the chamber size, a probe with adjustable packer spacing and pumping capacity would offer flexibility in the sensitivity of the probe and application in aquifers with different matrix porosities.
5.3 Identification of Further Research:
Since this investigation formed an initial step in the development of the DFTT as a characterisation tool for fractured rock aquifers, the potential for further research remains vast, especially due to the near infinite number of potential scenarios which may arise in an application of the DFTT in a fractured rock environment.

Further research which would form a sensible progression from this project includes the following:

- Uniqueness of responses with respect to multiple single fractures.
- Response of the test in the presence of connected fracture networks.
- Influence of the matrix hydraulic conductivity upon the DFTT response. This may include the sensitivity to small changes (i.e. different P-T sands) or greater changes such as the application of the DFTT in fracture-flow driven materials, such as the cretaceous chalk or granite.
- Further development of the “Shape Factor” or some other descriptor of the breakthrough curve, based upon these further findings or a simply a different approach to describing the curves presented in this report.

Other research which could also be considered:

- The effect of background gradients upon the DFTT in fractured rocks.
- The use of reactive tracers to estimate biogeochemical properties of fractures.
- The effect of NAPLs within the dipole flow field.
- The effect of variable aperture connected fracture networks- for example wide aperture bedding planes and narrower vertical jointing
- The possibility of conducting the DFTT in fractured aquifers in wells with sand-packs, such as for inherited or non-bespoke wells. This may also provide merit as an intentional method for characterising fractures with apertures beyond the sensitivity of the probe.
6. References


Spence, MJ.; Bottrell, SB.; Thornton, SF.; Richnow, HH.; Spence, KH. (2005). Hydrochemical and isotopic effects associated with petroleum fuel biodegradation pathways in a chalk aquifer. *Journal of Contaminant Hydrology*. **79**. 67-88


7. Appendices-

The following appendices are contained on the enclosed CD:

7.1. Example model input files.

7.2. BTCs and time series data.

7.3. BTC summary data sheet.

7.4. Online reference cache.