Abstract
The characterisation of the architecture of fault zones, where a damage zone around the major slip surface is composed of a complex array of minor faults, is only usually achievable via 2D maps, or 1D line samples or well logs. In this paper we address issues related to generating a 3D stochastic fault damage zone (FDZ) model that creates realistic fault systems resembling those encountered in nature, as well as developing a 3D fault flow model that can capture critical 3D upscaled properties of the damage zone.

The properties of interest to predict from the upscaling process include the bulk permeability of selected domains, the fault rock thickness on streamlines, the tortuosity and length of flow pathways, and the efficiency of the fault network in behaving as a barrier to the flow. Examining the fault rock thickness encountered on flow pathways across a major fault allows us to investigate the ‘effective’ fault rock thickness within the damage zone, thus allowing the contribution of the whole FDZ to be incorporated into a large-scale flow simulation. Therefore it is of interest to develop stochastic models generated for a range of the model control parameters, such as the fault length–frequency relationship, fault density, fault orientation distributions and spatial clustering.

In the flow model the throw to thickness ratio for individual faults is an input parameter to be specified, and thus the scalability of the effective thickness with this ratio is clearly of interest. Further, when considering fault systems of different characteristics, it is important to examine the relative influence of faults of different sizes on the effective FDZ thickness to determine the critical scales which must be modelled.

Based upon a vast sequence of simulations through the above framework, a summary of flow behaviours has been created which forms the basis for a predictive/uncertainty tool for the flow characteristics of cells used in reservoir simulation models.

Introduction
Bore-hole log and core measurements, as well as field observations of fault zones, have shown that major fault zones are surrounded by a region of minor faults that form the damage zone (Knipe et al. (1997, 1998)). The largest displacement occurs in the major slip zone, but, as the damage zone can have a major impact on the fluid flow, the slip zone and the damage zone both have to be accounted for when the impact of the fault is considered in reservoir-scale flow modelling (Caine and Forster (1999)). The faults and their damage zones may act as enhancers or retarders to fluid flow, and thus can have a great influence on the hydrocarbon distribution. Therefore, the investigation of the hydraulic properties of faults and their damage zones is of major interest in the hydrocarbon industry.

Seismic surveys allow us to identify major faults in reservoir fields, but little information can be acquired about the characteristics of their damage zones. In reservoir-scale models, major faults are often either represented by zones only one cell thick or incorporated in the properties of the boundary between two cells. Therefore, it is important to develop methodologies that can determine the bulk, or upscaled, hydraulic properties of the major faults and their damage zones from limited field data.

A stochastic model of a 3D FDZ was developed by Harris et al. (2003), and they used the model to examine the effect of the nature of the fault spatial distribution on the prediction of 3D fault...
population characteristics from 1D and 2D samples. Odling et al. (2004) employed a 2D discrete fracture flow model (DFFM) to determine upscaled properties of the damage zone created by the stochastic fault model.

It is of interest to assess the 3D upscaled flow properties of regions containing large numbers of faults acting as partial barriers to fluid flow, using the extension from 2D to 3D of the DFFM approach. It is also important to examine the significance of obtaining the 3D as opposed to the analogous 2D bulk properties when using these properties to characterize the damage zone.

A large database of fault damage zones and flow simulations on these zones has been generated for a set of combinations of both the FDZ and DFFM model parameters. For each flow model applied to a part of the fault zone, a number of flow properties are generated, and thus we can use this property distribution to predict flow behaviour for different model characteristics. Based on the FDZ model characteristics, this property distribution can serve as input for flow modelling in reservoir simulators.

**Fault damage zone and flow modelling characteristics**

A number of studies in the last decade have focused on the architecture of fault damage zones in both crystalline and siliclastic sedimentary rocks and their potential influence on fluid flow (see, for example, Antonellini and Aydin (1995)). These studies have analysed the fault network geometry of major faults and their damage zones. In siliclastic sedimentary rocks, faults take the form of deformation bands, along which grain size and porosity are reduced, under sufficient effective stress, to form a partial barrier to fluid flow (Fisher and Knipe (1998)).

The impact of the FDZ on fluid flow depends on the spatial variation in the fault rock petrophysical properties, the geometry of the fault network, and particularly on its connectivity, which is controlled by characteristics such as the fault size distribution, the fault density and the nature of the fault spatial distribution (Knipe et al. (1998)). To fully understand connectivity within a FDZ, knowledge of the 3D network is required. The connectivity of the subseismic fault network within the damage zone and the permeability contrast between the fault rock and rock matrix are major factors which influence the effectiveness of the damage zone as a barrier to fluid flow.

The FDZ model and the 3D DFFM model require a number of input parameters to be specified. These control the characteristics of the fault population within the damage zone, as well as the location and size of the regions within the FDZ where the flow model is applied. The hierarchical approach for spatial clustering in the FDZ that is employed here is fully described and validated in Harris et al. (2003) and therefore only a brief description is given here. The key parameters controlling the stochastic process of creating the FDZ are the following:

- The power law fault length–frequency exponent. Fault length is assumed to follow a power law distribution in which the exponent may be varied. In our study the 3D exponents of 1.6, 2.0 and 2.4 have been chosen to create fault systems, and these are considered to span the range of exponents that are of most interest. However, other, intermediate values may also be of interest. The major fault modelled has a throw of ~20–30 m.

- The fault orientation distributions. The strike and dip of the faults are each assumed to be normally distributed with mean orientation equal to that of a larger fault slip plane (in the fault creation process each fault is clustered around a larger fault, and this fault is used to define the orientation settings of the actual fault). The standard deviations of the fault strike and dip distributions are each set to either 5°, 10° or 15° in our investigations. The overall variation in fault orientation within the damage zone is complex and the model is typical of that observed in nature, allowing faults within the simulated damage zone to intersect and
form connected networks. In order to model a more complex geometry, a second approach is also considered for the dip orientation, where in addition to the main fault orientation we have added two other orientations to include faults dipping at ±30º to the main fault. This latter approach allows capturing the impact of anastomosing faults.

- The density of the faults. This is directly controlled by the number of faults $N$ that are present in the fault population, and correlation with the power law exponent is required (for larger values of the power law exponent, larger fault densities are required due to the increasing proportion of small faults and this number can be calibrated using synthetic cores through the FDZ).

- The size of the smallest fault possible in the fault population. Based on various model tests, a length of 2.5 m is considered to be small enough to capture the relevant characteristics of the damage zone that are related to the fluid flow, such as upscaled properties of regions within the damage zone.

Each fault is modelled as an ellipse with a horizontal long axis and an aspect ratio that follows a Gaussian distribution with a mean of 2 and a standard deviation of 0.05. The aspect ratio of 2 is typical of isolated normal faults. Also, a linear relationship between fault thickness and long-axis length is used, with a typical thickness:length ratio of $1:10^4$. A simple model for the thickness distribution over the fault plane is applied in which the thickness is a maximum at the fault centre and decreases linearly in all directions toward the fault tip line. This approximates the distribution of throw seen in isolated faults (Childs et al. (1995)). The effects of fault interaction on throw are not considered in the present model.

The DFFM approach employs simple control-volume and mass conservation techniques on regular orthogonal grids to enable large numbers of faults to be represented. Combined with the stochastic model for generating the 3D FDZ, the 3D DFFM is an essential tool for assessing the impact of complex fault networks on flow and determining upscaled properties of grid cells that would be included within a large-scale reservoir simulation package.

The most influential parameter in the flow model is the fault rock/host rock permeability contrast, $k_f / k_m$. In the present flow model we assume a uniform matrix permeability and a constant fault permeability. Another parameter for the DFFM model, the ratio of the fault length to the maximum fault thickness, has been set to $10^4$ in most investigations, which implies both the length:throw and the throw:maximum thickness ratios to be 100. However, the effect of the throw:maximum thickness ratio on the flow simulation results has been investigated, and results are presented later in the paper.

**Flow properties**

By modelling the flow using the DFFM model, the primary output is the upscaled permeability and the volume of fault rock in selected domains sampled within the FDZ.

The calculation of the fault rock volume within the selected domains in the FDZ allows the efficiency of these domains to be characterised in terms of the 3D upscaled permeability that would be obtained for a single fault of the same volume, which has a uniform thickness, spans the whole domain, and is perpendicular to the predefined flow direction. Thus the 3D bulk permeability of the sample domain, $\bar{k}_v$, can be approximated (see Pickup et al. (1995)) by the harmonic average of the fault rock and the matrix permeabilities:

$$\frac{A}{\bar{k}_v} = \frac{a}{k_f} + \frac{A-a}{k_m}$$

where $a$ is the uniform thickness of the fault and $A$ is the length of the sample region in the predefined flow direction. In this configuration, the fault rock is being utilised in the most efficient way by means
of acting as a barrier to the flow perpendicular to the fault. However, the bulk permeability is underestimated in this manner as it assumes uni-directional flow perpendicular to the single fault. In reality, the flow follows a tortuous pathway and tries to find a balance between the shortest pathway across the domain and the minimum fault rock which must be crossed when traversing the domain. Therefore, we provide a measure for the ‘efficiency’ of the fault arrangements in 3D by comparing the 3D flow with this idealised situation (see Odling et al. (2004)). Following the equation for the approximated value of the bulk permeability, the efficiency is defined as \[ \alpha = \frac{1}{K_x} - 1 \times \left[ \frac{a}{A(1/r-1)} \right] \], where \( r \) is the ratio of the fault to the matrix permeability and \( K_x = \frac{k_f}{k_m} \). The fault system (with or without the main slip surface) collapsed to a single fault represents 100% efficiency (\( \alpha = 1 \) in this case), and thus realistic fault arrangements will always result in lower levels of efficiency as the 3D upscaled permeability increases in these situations. The efficiency defined in this manner is a useful tool to characterize the FDZ in terms of fault arrays within sample domains, in addition to the upscaled permeability of these domains.

Another flow property of interest is the pathway distribution across the region. A number of pathways are simulated from the high-pressure interface of the sampled domain to the low-pressure interface. The number of faults crossed, the fault rock thickness on each simulated flow pathway, and the length of the flow pathway are recorded, and statistical data is obtained on the distribution of the flow pathway lengths and the distribution of the fault rock thickness on flow pathways. Thus, the minimum, the maximum, the mean, the variance and the standard deviation of these data distributions can be assessed.

When the flow pathways cross a 3D region, two principles prevail: (i) the flow pathways try to avoid as much (low permeability) fault rock as possible and so this property is minimised to a certain extent along routes through the domain; (ii) it may be more efficient to cross the fault at some location. According to the permeability contrast between the faults and the matrix, these two processes have different levels of influence. If \( k_f / k_m \) is very small then cross-fault flow is inefficient and flow pathways become tortuous, attempting to reduce the fault rock thickness encountered.

Comparison of FDZ model characteristics — sampling and examples

As the whole FDZ is statistically symmetrical, we only consider one half of the FDZ for modelling purposes, such that the FDZ is bounded by the major fault on the right. For the flow modelling in the damage zone, the major fault is not taken into account; however, the effect of the major fault on the various flow properties can be estimated analytically.

Figure 1 presents two-dimensional vertical cross-sections of FDZs, using a power law exponent \( D_3 = 2 \) and \( N = 3.6 \) million faults. The standard deviation of the fault strike and dip distributions is \( \sigma = 5^\circ \), and the dip orientations are either controlled only by the main fault or also by the dip direction of \( \pm 30^\circ \) from the main fault. The influence of the dip distribution on the FDZ realisation is clearly apparent, as in (a) the faults are in a relatively subparallel arrangement, whilst in (b) a higher degree of fault connectivity is observed. We expect that the flow across the region will cross generally less fault rock in case (b), because in case (a), due to the subparallel arrangement, fewer faults can be avoided.

The value of the power law exponent influences the proportion of small to large faults. Thus, whilst for \( D_3 = 1.6 \) the fault traces are highly connected, for \( D_3 = 2.0 \) the fault clusters can be more clearly identified, and also regions of very low fault density appear. When \( D_3 = 2.4 \), the fault clustering is even more obvious, a very large number of small faults is apparent, and a
relatively easy passage is expected for the flow across the region, with less fault rock on the flow paths when crossing the damage zone. The examination of the FDZ by two-dimensional vertical cross-sections of the type in Figure 1 is a useful tool in estimating the degree of connectedness and efficiency of various regions, as well as the fault density and heterogeneity of the FDZ.

Figure 1: Vertical cross-sections of FDZs using fault orientation models for $D_3 = 2$ and $N = 3.6$ million: (a) orientation controlled by main fault (with $\sigma = 5^\circ$); (b) added preferred dip direction of $\pm 30^\circ$ (with $\sigma = 5^\circ$).

The proportion of small and large faults in a fault population is also investigated along flow pathways which cross the sample domain, starting at the centre point of the high-pressure interface. From the information recorded for the faults on these flow pathways, the percentage of faults smaller than a given length is calculated, and thus the distribution of faults of different sizes can be assessed. By comparing the results for the different power law exponents, it is apparent that for $D_3 = 1.6$ the faults smaller than 10 m in length make up less than about 20% of the total number of faults on the flow pathway, and this observation is nearly independent of the standard deviation of fault strike and dip and the permeability contrast. Analogous observations are made for $D_3 = 2.0$ and 2.4, where the faults smaller than 10 m in length account for about 30–40% and 45–55%, respectively.

Figure 2 shows the contributions by faults of different sizes to the fault rock thickness on flow pathways crossing the FDZ. The percentage of fault rock thickness contributed by faults smaller than a given length has been calculated for the power law fault length–frequency exponents of (a) $D_3 = 1.6$, (b) 2.0 and (c) 2.4, for a flow pathway crossing the zone near the centre of the main fault, where the throw is 30 m, and the size of the confining region is 80 m × 50 m × 20 m. The dip orientation of the faults is controlled by the main fault. The black, blue and red lines are for the results obtained for the standard deviation of strike and dip of $5^\circ$, $10^\circ$ and $15^\circ$, respectively, whilst the continuous, the dashed and the dotted lines are for the fault to matrix permeability contrasts of $10^{-3}$, $10^{-4}$ and $10^{-5}$, respectively.

In Figure 2, the significance of faults of different sizes, particularly the smallest fault size, on the fault rock thickness on flow pathways across the FDZ can be assessed, and the question of whether a cut-off of 2.5 m captures the correct fault thickness along flow pathways for the FDZ can be answered. It is observed that for $D_3 = 1.6$ the faults smaller than 10 m in length make up for less than about 0.5% of the total fault rock thickness on the flow pathways, whilst for $D_3 = 2.0$ and 2.4 these percentages increase to about 2–3% and 5–8%, respectively. Thus, faults smaller than 10 m in length have a relatively small contribution to the fault rock thickness on flow pathways, especially for $D_3 = 1.6$ and 2.0. For $D_3 = 2.4$ the fault rock percentage is slightly
higher, but also the number of faults smaller than 10 m increases significantly. From the above data we conclude that it is appropriate to set the size of the smallest modelled fault in the population to be 2.5 m. However, it is also concluded that excluding faults of length 2.5 m to 10 m would be significant.

It is worth noting that the relative influences of faults of different sizes do not show significant variation with the standard deviations of fault strike and dip and the permeability contrast.

In Figure 3 the variation of the fault rock thickness of the FDZ along flow pathways has been investigated as a function of the fault length to thickness ratio on individual faults. The issues of whether the fault rock thickness can be scaled, and what is the effect of varying the power law exponent, are to be addressed.

If we model the flow in a chosen 3D region for different values of the fault throw to thickness ratio but keep the same fault distribution, then the flow paths through the region would vary to a certain extent, as when the faults are thicker the flow chooses a different path across the region. Thus, it is of interest to assess the extent to which these flow paths would vary as the fault throw to thickness ratio varies. Flow runs have been performed for various values of the fault throw to thickness ratio, and the results obtained for a fixed value of this ratio have also been extrapolated. The extrapolation procedure is based on the assumption that the flow would follow the same path if in the sample region the thickness of every individual fault was scaled (by varying the throw to thickness ratio). Figure 3 shows results for the power law exponent $D_3 = 1.6$. 

![Figure 2: Percentage of fault rock thickness contributed by faults smaller than a given length (the various lines are for different orientation models and permeability contrasts).](image)

![Figure 3: Scaling of fault rock thickness with the throw:thickness ratio ($k_f/k_w = 10^{-4}$).](image)
and for a fault to matrix permeability ratio of $10^{-4}$. The continuous line shows the results when obtained directly by the DFFM model for throw to thickness ratios of $4 \times 10^1, 6 \times 10^1, 8 \times 10^1$, $10^2, 1.3 \times 10^2, 1.6 \times 10^2$ and $2 \times 10^2$, whilst the crosses show extrapolated results based on those obtained for the throw to thickness ratio $10^2$ (‘base case’). Only a maximum relative difference of 0.2% is observed between the modelled and the extrapolated results (for the investigated range of throw to thickness ratios with the results extrapolated from those obtained for the ‘base case’), and thus we conclude that the results for the fault rock thickness on the flow pathways through sampled 3D regions can be reliably scaled up for values of the fault throw to thickness ratio in the range of $4 \times 10^1$ to $2 \times 10^2$.

The variation of the 3D flow properties in the DFFM model is analysed in Figure 4 as the permeability contrast varies between $10^{-3}$ and $10^{-6}$. The fault strike and dip distributions have a standard deviation of $10^\circ$. It is observed in Figure 4(a) that the bulk permeability $k_f$ increases with increasing permeability contrast and it approaches a constant value as the permeability contrast decreases. Thus, for very low values of $k_f$ the bulk permeability is directly proportional to $k_f$.

Statistical data on the flow pathway lengths across the selected sample region are also plotted in Figure 4(b). For all three power law exponents, the flow pathway lengths increase with the permeability contrast and the extent of this rise is more accentuated for larger power laws, as observed from the mean of the results. Thus, the largest path lengths are found for $D_3 = 2.4$ and $k_f / k_m = 10^{-6}$, and this is explained by the larger proportion of small faults in the population compared to $D_3 = 1.6$ so that the flow pathways can follow a more tortuous route, whilst for $D_3 = 1.6$ the flow is dominated by large faults.

Comparing 2D and 3D flow simulations

Results for (a) the normalised bulk permeability and (b) the efficiency of a selected domain of the fault zone are presented in Figure 5 for $k_f / k_m = 10^{-4}$. A domain of size 50 m by 50 m in the $x$ and $y$ directions is chosen, whilst the region size in the $z$ direction is either 0.1 m, 1 m, 20 m or 50 m. It is apparent from the upscaled permeability plots that, as the domain height increases from 20 m to 50 m, the bulk permeability generally increases. This is to be expected as the flow has more freedom in crossing the domain for increased domain height, and the fault rock thickness on flow pathways generally decreases. The trend in the efficiency variation is similar in that the efficiency decreases for a greater domain height, and again this is expected as larger domains would form less effective barriers to the flow through them because of the fault population and clustering characteristics. Based on the above observations, we conclude that the spatial characteristics of the FDZ within 2D and 3D domains are a significant factor in influencing the flow properties of these domains.

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Concluding remarks

A set of 3D stochastic FDZs has been generated for a range of control parameters, such as the power law fault size–frequency exponent, the fault strike and dip orientations, and the fault density within the fault population. This allows us to calibrate the FDZ model output with field observations and predict general characteristics for the whole FDZ, such as fault density distribution, fault connectivity and fault clustering characteristics. The 3D DFFM model allows us to predict 3D upscaled flow properties for a FDZ, such as the upscaled permeability, the efficiency of the fault array in acting as a flow barrier, the length and tortuosity of flow paths, and the fault rock thickness on flow paths.

A large sequence of simulations of the FDZs and their 3D flow characteristics has been generated when the faults act as partial flow barriers, and this provides a source for queries over a large set of control parameters.

Improvements on the simple assumptions made here would be to consider layered stratigraphy and variable fault permeability. However, considering that the present flow model is a one-phase flow model, the current approximations are considered sufficient to give a qualitative inquiry of the 3D flow properties within FDZs, and constitute a starting point for further flow investigations involving multiphase flow and layered stratigraphy.

References


