Seismic response of fractures by numerical simulation

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SUMMARY
Fractures occur on a wide range of scales and are important in the study of hydrocarbon reservoirs. Seismic simulation by finite-difference modelling using an equivalent medium method can devise the elastic parameters of a cell intersected by a fracture as those of a medium with an equivalent seismic response. Numerical experiments confirm that diffractions from the fracture tips are a strong component of the total wavefield. However, a comparison of boxcar, linear, angular and elliptic tapering suggests that there is little dependence on shape because the energy involved in a single diffraction is much lower than the incident energy. An open, fluid filled fracture has stronger effect on the wavefield than the wet and dry, multiple crack models, because an open fracture would have a stronger dissimilarity to the background rock. The density of microcracks within a fracture also has strong effect on the seismic response, however the properties of those cracks are not significant to the overall seismic response. Considering a distribution of a large number of fractures, even when the overall density of fractures is held constant, longer fractures attenuate seismic energy more than smaller ones. For the orientation effect, fractures oriented in the direction of propagation seem to affect the wavefield more than those perpendicular because of the incident wave striking the fracture at an angle greater than the critical angle. Experiments on clustering of the fractures indicate that although clusters which are large compared to the wavelength may attenuate and ‘shield’ more than for a uniform distribution, smaller ones in fact attenuate less, because of the ‘healing’ effect. These are important results when trying to characterize the fracture properties including density, clustering, size and orientation of a fractured reservoir from field seismic data.

Key words: Computational seismology; Wave scattering and diffraction; Wave propagation.

1 INTRODUCTION
Fractures are important features of hydrocarbon reservoirs and should be included in seismic simulation. However, the scale on which they can occur is often far smaller than the grid size in numerical modelling, and it is necessary to consider how to introduce them computationally.

A common method for simulating seismic response of fractures is the equivalent medium method, which works on two levels. The first is physical, used where a larger fracture is made of small cracks to find an expression for the total fracture in the form of a medium with an equivalent seismic response (Hudson & Knopoff 1989). The second is computational, seeking to replace finite-difference cells intersected by fractures with those of a medium with an equivalent seismic response. Coates & Schoenberg (1995) applied this method to a finite-difference situation which requires no special treatment of displacement discontinuity conditions on the fractures (Saenger & Shapiro 2002; Saenger et al. 2004). Schoenberg & Sayers (1995) argued that the method was only truly valid in the long wavelength limit, as the applied stress was assumed to be constant over the fracture. However, in a comparison of this method to one where the fracture was explicitly defined (Wu et al. 2005), the two methods showed good agreement, even when the wavelength was much shorter than the fracture length, and indeed the method is frequently applied in situations where the wavelength is shorter than the fracture length (Coates & Schoenberg 1995; Vlastos et al. 2003; Wu et al. 2005). The equivalent medium method in a finite difference situation requires the use of the linear slip approximation, where the displacement discontinuity because of a fracture is assumed to be linearly related to the traction, this approximation is supported by experimental results (Pyrak-Nolte et al. 1990; Hsu & Schoenberg 1993).

The comparison of the wavefield produced by a single fracture generated analytically and by forward modelling conducted by Krüger et al. (2005) shows that it is possible for a finite difference method to accurately reproduce the seismic response of a fracture.

Finite-difference studies of the seismic responses of sets of randomly distributed fractures have used the equivalent medium method to observe the effects of fracture distribution and extent on
a set of fractures in a constant velocity medium (Vlastos et al. 2003; Murai 2007). They indicate that the size of the fractures strongly affects the resultant waveform, with fractures shorter than wavelength acting more as scatterers and longer ones more as reflectors. A finite-difference scheme can also be used when the fractures are not aligned (Orlowsky et al. 2003). Strong differences were also observed in wavefields produced by different clustering of random distributions. A fracture system can evolve with time, and thus so will the resultant wavefield (Vlastos et al. 2007).

The scattering of waves caused by fractures can be used to produce synthetic transfer functions, which can then be used to estimate fracture orientation (Willis et al. 2006). The method is applied to field data and shows good agreement with other anisotropy studies. Rao & Wang (2009) have shown that fractures can also be located by full waveform inversion, indicating the importance of knowing how the properties of fractures can affect the waveform and being able to model this accurately in the forward modelling stage.

It is possible to include into an equivalent medium formulation a method for considering porosity (e.g. Toms et al. 2006; Ponomarev & Nagornov 2010) and double porosity (Markov et al. 2005). Vlastos et al. (2006) consider the effects of an injection of fluid, by modelling how the pore pressure changes, and show that the effects can be detected in the wavefield from finite-difference modelling.

In this paper, first we recap the computational equivalent medium method, and summarize the methods used to calculate the fracture compliance. Then we apply these methods to synthetic forward modelling examples to test the effect of fracture structure on results. Finally, we test the effects of fracture shape, orientation and distribution.

2 THE EQUIVALENT MEDIUM METHOD

Hooke’s law relates stress and strain as

\[
\tau_{ij} = c_{ijkl} e_{kl},
\]

where \(\tau_{ij}\) is stress, \(c_{ijkl}\) is the elastic tensor and \(e_{ij}\) is strain. In the equivalent medium theory, the elastic tensor \(c_{ijkl}\) in eq. (1) is defined as

\[
\begin{align*}
    c_{11} &= (\lambda + 2\mu) (1 - \delta_N), \\
    c_{33} &= (\lambda + 2\mu) (1 - r^2\delta_N), \\
    c_{13} &= \lambda (1 - \delta_N), \\
    c_{35} &= \mu (1 - \delta_T), \\
    c_{15} &= c_{35} = 0,
\end{align*}
\]

(2)

where

\[
\begin{align*}
    r &= \frac{\lambda}{\lambda + 2\mu}, \\
    \delta_N &= \frac{Z_N (\lambda + 2\mu)}{L + Z_N (\lambda + 2\mu)}, \\
    \delta_T &= \frac{Z_T \mu}{L + Z_T \mu},
\end{align*}
\]

(3)

and \(Z_N\) and \(Z_T\) are the elements of the fracture compliance matrix \(Z\) as (Schoenberg 1980)

\[
Z = \begin{bmatrix}
    Z_N & 0 \\
    0 & Z_T
\end{bmatrix}.
\]

(4)

Note that the compliance matrix here is specifically related to the fractures and is not the compliance tensor, the inverse of the elastic tensor.

When \(\delta_N\) and \(\delta_T\) are equal to be zero, where there are no fractures, eq. (2) reduces to the elastic constants for a finite-difference cell.
containing only the isotropic background material, as
\[ c_{11} = c_{33} = \lambda + 2\mu, \]
\[ c_{13} = \lambda, \quad c_{55} = \mu, \]
\[ c_{15} = c_{35} = 0. \]

We list three fracture compliance models as the following.

2.1 Fractures as displacement increases

To simply add in extra displacement to a horizontal fracture, Coates & Schoenberg (1995) used fracture compliances of
\[ Z_N = \frac{\alpha_N h}{c_{11}}, \quad Z_T = \frac{\alpha_T h}{c_{55}}. \]
where $h$ is the finite-difference cell size and $\alpha$ is the fraction by which the displacement is to be increased. For example, to increase displacement by 10 per cent, $\alpha = 0.1$. As the parameter $\alpha$ is somewhat arbitrary, this is not closely related to the physics of the situation.

### 2.2 Fractures as open, fluid filled structures

For an open, fluid filled fracture,

$$Z_N = \frac{\gamma c a^3}{\mu} A_T,$$

$$Z_T = \frac{\gamma c a^3}{\mu} A_N,$$

(7)

where $h$ is the width of the fracture and $K$ is the Bulk modulus of the fluid (Wu et al. 2005).

### 2.3 Fractures as regions of isolated slip

The model of Liu et al. (2000) considers the fracture as a planar distribution of small isolated areas of slip. The method is developed in the long wavelength limit. The small areas of slip are referred to as cracks. They use the fracture parameters

$$A_T = U_{11} \left[ 1 + \left( \gamma c a^2 \right)^{3/2} \frac{\pi}{4} \left( 3 - \frac{2 \beta^2}{\alpha^2} \right) \right],$$

$$A_N = U_{33} \left[ 1 + \left( \gamma c a^2 \right)^{3/2} \frac{\pi}{4} \left( 1 - \frac{2 \beta^2}{\alpha^2} \right) \right],$$

(8)

where $\gamma$ is the number of cracks per unit area, $a$ is the average radius of a crack and

$\alpha$ and $\beta$ are the $P$- and $S$-wave velocities of the background rock, and $U_{11}$ and $U_{33}$ correspond to the response of a single crack to shear traction and tension. These equations are derived by Hudson et al. (1996), based on the principle of averaging the scattered waves from the cracks developed in Hudson (1980). In this case

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**Figure 4.** Difference between energy in reflected waves in wet and dry cases.

**Table 1.** Quantifying model results by a simple coherence analysis. The coherence quantity is the energy summing along the wave front of the first arrival, and normalized against that along the direct wave front without any fractures.

<table>
<thead>
<tr>
<th>Model</th>
<th>Coherence in horizontal component</th>
<th>Coherence in vertical component</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical fractures</td>
<td>0.22</td>
<td>0.34</td>
</tr>
<tr>
<td>Horizontal fractures</td>
<td>0.45</td>
<td>0.23</td>
</tr>
<tr>
<td>45° (bottom right)</td>
<td>0.06</td>
<td>0.38</td>
</tr>
<tr>
<td>45° (bottom left)</td>
<td>0.33</td>
<td>0.54</td>
</tr>
<tr>
<td>Short fractures</td>
<td>0.98</td>
<td>0.86</td>
</tr>
<tr>
<td>Medium fractures</td>
<td>0.63</td>
<td>0.47</td>
</tr>
<tr>
<td>Long fractures</td>
<td>0.46</td>
<td>0.29</td>
</tr>
<tr>
<td>Wide Gaussian cluster</td>
<td>0.73</td>
<td>0.59</td>
</tr>
<tr>
<td>Narrow Gaussian cluster</td>
<td>0.98</td>
<td>0.90</td>
</tr>
<tr>
<td>Uniform random</td>
<td>0.93</td>
<td>0.79</td>
</tr>
</tbody>
</table>

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**Figure 5.** Fracture models for a random distribution. (a) The length of fractures is $0.1 \lambda$, where $\lambda$ is the wavelength. (b) The length of fractures is $\lambda$. (c) The length of fractures is $4 \lambda$. The fracture density of these three models is constant.
\[ c_{11} = (\lambda + 2\mu) \left( 1 + \frac{\lambda + 2\mu}{\mu} \varepsilon U_{33} \right)^{-1}, \]
\[ c_{33} = (\lambda + 2\mu) \left( 1 + 4\varepsilon U_{33} \right) \left( 1 + \frac{\lambda + 2\mu}{\mu} \varepsilon U_{33} \right)^{-1}, \]
\[ c_{13} = \lambda \left( 1 + \frac{\lambda + 2\mu}{\mu} \varepsilon U_{33} \right)^{-1}, \]
\[ c_{55} = \mu \left( 1 + \varepsilon U_{11} \right)^{-1}, \]

(10)

Figure 6. Snapshots of the horizontal (left) and vertical (right) components of velocity for the models in Fig. 5.
where \( \varepsilon \) is the volume density of cracks within the fracture, it is assumed to be small as the equations are only valid to first order. For wet fractures (Hudson 1981),

\[
U_{11} = \frac{16}{3} \frac{\lambda + 2\mu}{\lambda + 4\mu}, \quad U_{13} = 0.
\]  

(11)

And for dry fractures

\[
U_{11} = \frac{16}{3} \frac{\lambda + 2\mu}{\lambda + 4\mu}, \quad U_{13} = \frac{4}{3} \frac{\lambda + 2\mu}{\lambda + \mu}.
\]  

(12)

These expressions can be adapted to situations where the fracture is mostly unwelded (Hudson & Liu 1999) and frequency dependant results where weak infill results in attenuation (Liu et al. 2000).

### 3 Fracture Shape, Orientation and Distribution

#### 3.1 Fracture tapering

The shape of a fracture, and the degree to which it tapers towards the fracture tips, is a characteristic whose effect on the seismic wavefield can be studied. To shape the fracture, the compliance matrix, \( Z \), of eq. (4) is multiplied by a tapering function, \( A \), that is

\[
Z_{TOTAL} = AZ.
\]  

(13)

The simplest function for \( A \) is a boxcar shape (Coates & Schoenberg 1995)

\[
A(x) = 1, \quad -L/2 < x < L/2,
\]  

(14)

where \( L \) is the length of the fracture and \( x \) is the coordinate along it, with the origin in the centre. Another commonly used shape is an ellipse, as

\[
A(x) = \left[ 1 - \left( \frac{x}{L/2} \right)^2 \right]^{1/2}.
\]  

(15)

Another alternative is linear tapering, either along the whole fracture

\[
A(x < 0) = \frac{x}{L/2} + 1, \quad A(x > 0) = \frac{-x}{L/2} + 1,
\]  

(16)

or at a given angle from the fracture tip (Choupani 2009). Unlike linear or elliptic shaping, tapering at a fixed angle will not depend on the fracture length. Fig. 1 shows a graph illustrating the tapering functions.

An analysis of the effect of tapering by Vlastos et al. (2003) indicates that fracture tapering causes small differences in the amplitude of the fracture wavefield, particularly in the S-wave-to-S-wave reflected component. A finite element study in 3-D of fracture shape by Grechka et al. (2006) concluded that fracture shape was not important in the overall properties of rock.

#### 3.2 Fracture orientation

The angles between source, fracture and receiver will have a strong effect on the seismic response (Rao & Wang 2009). The Love notation of the elastic constant as second order \( c_{ijkl} \), although a convenient form, is not a true second order tensor and cannot be rotated as such in the finite difference grid. It is necessary to return to the full, fourth order tensor \( c'_{ijkl} \) which can be rotated as

\[
c'_{ijkl} = R_{ip} R_{jq} R_{kr} R_{ls} c_{pqrs},
\]  

(17)

where \( R \) is the rotation matrix for an angle \( \theta \) which in two dimensions has the components

\[
R = \begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix}.
\]  

(18)

#### 3.3 Distributions of fractures

The work of Vlastos et al. (2003) considered the effect of fracture length compared to wavelength, and found that for small fractures, scattering is the most important feature in the wavefield, but for longer fractures the effect on the wavefield is more complicated. They also looked at distributions of large numbers of aligned fractures. The distributions used were random uniform, Gaussian, exponential and Gamma. They found that spatial distribution has a great effect on the resultant wavefield. A uniform, random distribution is commonly used in fracture modelling (e.g. Rao & Wang 2009). The results indicate that clustering of fractures close to the source can contain much of the seismic energy through shielding, an effect also shown by Orlowsky et al. (2003). However, if the clusters are very small, they can in fact attenuate less than a uniform distribution.

### 4 Implementation and Results

#### 4.1 Fracture and source locations

To study the effects of fracture properties on synthetic seismic results, we write a program to calculate the elastic constants in the equivalent medium method of Coates & Schoenberg (1995). We then model the response of this system using the finite-difference

Figure 7. Fracture models for a random distribution of fractures. (a) Horizontal fractures, (b) vertical fractures, and (c) 45° fractures.
forward modelling scheme of Levander (1988). To maximize the effects of the fractures, the background rock is assumed to be isotropic and homogeneous. The material parameters are as in Wu et al. (2005), that is, the background has $V_P = 4200 \text{ m s}^{-1}$, $V_S = 2700 \text{ m s}^{-1}$, density $\rho = 2490 \text{ kg m}^{-3}$, the fracture has $V_P = 1500 \text{ m s}^{-1}$, $V_S = 0$, density $\rho = 1000 \text{ kg m}^{-3}$ and the modelling parameters are $dx = dz = 0.06 \text{ m}$, $dt = 0.008 \text{ ms}$, peak frequency = 3000 Hz. The fracture is modelled as being open and fluid filled, of width 4 mm.

The model used for a single fracture, and a snapshot of the waveform with arrivals identified are shown in Fig. 2. The arrivals

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Figure 8. Snapshots of the horizontal (left) and vertical (right) components of velocity for the model in Fig. 7.
in Fig. 2 are identified as the P- and S-wave reflections from the fracture body (PPr, PSr) and the transmitted P to S converted wave (PSt). Also visible are the P- and S-wave diffractions from the tip and the head wave.

4.2 Effects of tapering on a single fracture

To examine the effects of the shape of a fracture upon the resultant wavefield, we use the model shown in Fig. 2. The model is run, with the same parameters, in cases where the fracture is boxcar shaped (eq. 14), elliptically tapered (eq. 15), linearly tapered along the whole fracture towards the tips (eq. 16) and tapered at the tips with an angle of $15^\circ$. The direct wave is subtracted from the results, then the horizontal and vertical components of velocity are squared and added to calculate the energy. The boxcar is used as a reference, the difference is calculated between the boxcar wavefield and that of each of the other models. The absolute values of the energy difference at each point of the wavefield are then summed across the snapshot, and expressed as a percentage of the energy of the boxcar response. The results are listed as the following:

<table>
<thead>
<tr>
<th>Model</th>
<th>Difference from boxcar model (per cent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear</td>
<td>0.349</td>
</tr>
<tr>
<td>Elliptic</td>
<td>0.046</td>
</tr>
<tr>
<td>$15^\circ$</td>
<td>0.006</td>
</tr>
</tbody>
</table>

These results indicate that the differences are very small. This apparent lack of dependence on tapering agrees with the finite element study of fracture shapes in 3-D by Grechka et al. (2006), which also finds that the overall shape is not an important characteristic of a fracture. The very small differences may correspond to the slight differences observed by Vlastos et al. (2003).

4.3 Effects of the fracture compliance model

The same model of a single fracture and source as used in Fig. 2 is employed to consider the effect of the model used to calculate the fracture compliance. The fracture orientation is chosen to be able to see the effects of the fracture body. An elliptic tapering is applied in all models. The three fracture compliance models considered are for the open, water filled fracture of Wu et al. (2005), the wet, isolated areas of linear slip of Hudson (1981) and the dry, isolated areas of linear slip of Hudson (1981). The parameters in the first case are as in Section 4.1. The parameters for the second and third cases are that the material velocities and density of the fracture are as for the background rock, and the crack density $\varepsilon$ which controls the proportion of the fracture allowed to slip is set to 0.3, implying that slip areas account for 30 per cent of the total fracture area. This is a larger value than is recommended in the development of the method, as the equations are only valid to first order in $\varepsilon$ however it is used to maximize the response of the fracture for comparison of the methods.

As can be seen in Fig. 3, the open fracture has a much stronger response than either of the isolated slip models, this as would be expected from the fact that the difference between the fracture and the background rock is much greater. The difference between the wet and dry models is not immediately obvious, so the receiver response is used to calculate the difference. The energy of the difference is shown in Fig. 4, however the total energy in this seismogram is 3.2 per cent of the energy in the original (with direct wave removed) therefore overall the difference between the models is very slight, and unlikely to be observable in real life.

A study of the effect of changing the crack density $\varepsilon$ is important, as there is a great deal of controversy about the maximum value of the crack density for which the Hudson models are valid. The equations are only calculated to first order in crack density, and expected to be valid for $\varepsilon < 0.1$, however it has been suggested that the threshold may be as low as $\varepsilon < 0.01$ (Grechka 2005), otherwise the method significantly overestimates effective parameters. On the other hand, comparison to laboratory data suggests the equations give good results for $\varepsilon < 0.07$ (Ass’ad et al. 1992). We test to see the effect of changing crack density from situations where the model is likely to be invalid to situations where it is likely to be valid, using values for $\varepsilon$ of 0.3, 0.1, 0.05 and 0.01. The results are expressed using the 0.01 case as a reference, and the difference in energy is calculated and expressed as a multiple of that case:

<table>
<thead>
<tr>
<th>$\varepsilon$</th>
<th>Energy difference (multiple of $\varepsilon = 0.01$ case)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>127</td>
</tr>
<tr>
<td>0.1</td>
<td>21</td>
</tr>
<tr>
<td>0.05</td>
<td>7</td>
</tr>
</tbody>
</table>

These results indicate that the parameter has a very clear effect on the fracture response, therefore the continuing debate over the correct physical value is an important one.

Figure 9. (a) Fracture model for a random distribution of fractures in uniform distribution, (b) Gaussian distribution with standard deviation $4\varepsilon$, and (c) Gaussian distribution with standard deviation $2\varepsilon$. 

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4.4 Effects of fracture distribution models

The studies into fracture sizes of Vlastos et al. (2003) indicate that, as would be expected, in the case of fractures smaller than wavelength the wavefield is dominated by scattering, and in the case of fractures larger than wavelength reflection becomes an important feature. However, their experiments kept the total number of fractures the same although increasing the fracture length. Their results showed that much less of the energy seems to be transmitted in the case of longer fractures, but it is not clear from their study whether this is because of a property of the fractures themselves, or whether it is because with the same number of fractures, longer ones will of course lead to a higher overall fracture density.

To quantify results of these models, a simple coherence analysis is conducted by summing along the wave front of the first arrival. As the source is a Ricker wavelet, it would be expected to show

Figure 10. Snapshots of the horizontal (left) and vertical (right) components of velocity for the models in Fig. 9.
a duration inversely related to the peak frequency. The window used is centred on the peak and is half the width of the wavelet, to remove the negative polarity side lobes of the Ricker wavelet. The summation occurs along the bottom right quadrant of the model in all cases except in the case of 45° orientation, where the bottom left is included for comparison. The coherences for all the multiple fracture models which follow are given in Table 1, in which the coherence quantities are normalized against the energy along the direct wave front without any fractures.

A study of fracture sizes keeping the overall fracture density the same, that is decreasing the number of fractures as their size increases, would be of interest, particularly as in many hydrocarbon exploration situations, fractured reservoirs are characterized by density (Agosta et al. 2010). In our experiments, we distribute fractures randomly in a uniform distribution, keeping the number density of finite-difference cells containing fractures constant (Fig. 5). Varying the fracture length from 0.1λ to 4λ, where λ is the wavelength, shows that even keeping the fracture density constant, fractures which are long compared to the wavelength attenuate more than those which are short (Fig. 6).

4.5 Effects of fracture orientations

Where the fracture length is less than or comparable to the wavelength, that is where the fracture is acting at least in part as a reflector, the orientation of fractures might be an important feature. To test this, we consider sets of fractures which are vertical, horizontal and at 45° (Fig. 7). These fractures are roughly in line with, perpendicular to and at 45° to the wave front, but not exact because the source is very close to the fractures so the wave front is curved. Nevertheless, these models are good enough to show key differences between the results from the different orientations (Fig. 8).

The horizontal fractures, which might intuitively be expected to have more effect, actually seem to affect the wave front less than vertical ones, that is the diffractions from the fractures are more disruptive than the reflections. This phenomenon has been observed elsewhere (Rao & Wang 2009), and is because of the incident wave front reaching the fracture at an angle greater than the critical angle, so more of the energy is released, decreasing the coherence. The 45° orientation result shows the directionality of the fractures well, indicating that this forward modelling method has potential in seismic inversion.

4.6 Effects of fracture clustering

The study in fracture distribution by Vlastos et al. (2003) indicated that clustering of fractures close to the source can contain much of the seismic energy, however, smaller clusters actually attenuate energy the least. To investigate the phenomenon of seismic healing, where the wavefield ‘heals’ after it has travelled through an anomaly (Zaroli et al. 2010) such as a fracture cluster, we use Gaussian clusters with different standard deviations (Fig. 9). A comparison of the resulting wavefields with that from a uniform distribution in the fracture region (Fig. 10), in which the total number of fractures is held constant, shows that the wavefield is better healed beyond smaller clusters than larger.

5 CONCLUSIONS

Fractures have been included in finite-difference forward modelling using an equivalent medium formulation. This method depends upon the fracture compliance, which is related to the physical properties of the fracture. There are simple equations for linear slip displacement discontinuity or an open, fluid filled fracture. More complicated models, for fractures consisting of small cracks in a welded area, can use a further equivalent medium representation, where the seismic response of the cracks is expressed for the fracture as a whole. Looking at snapshots of the wavefield produced by a fracture, the waves can be identified as P or S arrivals from the tip, reflections, transmitted and head wave.

The diffractions from the fracture tip are a strong component of the total wavefield, and the shape of the fracture may affect this, however, a comparison of the results from boxcar, elliptic, linear and angular tapering suggests that this is not an important consideration, as the changes are small compared to the overall wavefield.

A comparison of the wavefield produced from an open, fluid filled fracture and from the wet and dry, multiple crack models indicates that the former produces stronger effects than the latter. This is as might be expected, because an open fracture would have a stronger dissimilarity to the background rock. The two Hudson (1981) models showed very little difference, except in the amplitude of the reflected P wave. They depend on the crack density, the correct values of which are disputed in the literature, we have found that the seismic response is strongly dependant on the crack density.

A study of the effects of fracture length in a uniformly distributed set of fractures shows that longer fractures attenuate more than smaller fractures, even when fracture density is held constant, this is an important result when trying to characterize the fracture density of a fractured reservoir from seismic data. The orientation of the fractures is also considered, fractures oriented in the direction of propagation seem to affect the wavefield more than those perpendicular, as they are incident beyond the critical angle. Experiments on clustering of the fractures indicate that although large clusters may attenuate and ‘shield’ more than for a uniform distribution, smaller ones in fact attenuate less, because of the ‘healing’ effect.

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