Characteristics of seismic wavefields in fluid-saturated fractured rocks

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Characteristics of fractured media from seismic wavefields

**Motivation**

Measurement:
Recorded seismic wavefield

Seismic Attributes:
- Velocities
- Attenuation
- Anisotropic parameters

Properties of the fractured medium

Physical Mechanisms?

**Graph**

Amplitude

-0.5 0 0.5 1

Reflection from fractured zone

Reflection from fractured zone

Receiver 1

Fractured medium

Receiver 2

0 1 2 3 4 5 6

time [sec]

×10^{-3}
Scales

Laboratory data  |  Log data  |  Seismic data (VSP)
--- | --- | ---
MHz  |  Measurement frequency – seismic wavelength  |  Hz
cm  |  Spatial scales (fracture dimension)  |  km

“Despite these striking scale differences the physical mechanisms are similar “

Incident wave  

Fractured medium  

Transmitted wave  

Receiver 1

Reflected wave (transmission loss)  

Scattered waves  

Intrinsic attenuation

Receiver 2

Attenuation

\[ Q_p^{-1}(\omega) = Q_{transmission}^{-1}(\omega) + Q_{scattering}^{-1}(\omega) + Q_{intrinsic}^{-1}(\omega) \]
Can we link intrinsic attenuation to fracture network properties?

Numerical upscaling approach applied to stochastic fracture networks

- Wave propagation effects are ignored

The role played by wave propagation effects

A comparison of wave propagation modelling and numerical upscaling for simple models

Application to full wave-form sonic data
Intrinsic attenuation – in fractured fluid saturated media

**Background:** stiff porous matrix of low porosity and permeability

**Fractures:** compliant inclusion of high porosity and permeability

**Mechanism:** Pressure diffusion processes (fractures << seismic wavelength)

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**Attenuation magnitude:**
- Induced pressure gradients
- Fluid storage volume

**Time scale (frequency):**
- Hydraulic properties
- Fracture size
Stochastic fracture networks

Fracture network parameter: 

\[ n(l, L) = d_{frac}(a-1) \frac{l^{-a}}{l_{min}^{-a+1}} \text{ for } l \in [l_{min}, l_{max}] \]

**Constant aperture**

- **1.5% (20 networks)**
- **1.5% (20 networks)**
- **3.25% (20 networks)**

**Variable aperture**

- **12% (40 networks)**
Pressure fields

$a = 1.5$

$a = 3$
Attenuation trends: length distribution and fracture volume
Comparison constant vs. variable aperture: Attenuation trends vs. fracture volume

Fracture-to-fracture flow: Increase with fluid storage volume within fractures (larger apertures!) but not necessarily number of connections!
Conclusions

Establishing a direct relation between hydraulic conductivity and attenuation remains difficult!

Seismic attenuation depends on:
- Number of local connections
- Size of fracture cluster
- Fluid storage volume
- Elastic interaction between fractures
- Fracture length distribution
- Orientation of fractures (isotropic networks)

P-wave attenuation trends change close to percolation threshold
Sensitive to the degree of local fracture network connectivity but not to the existence of a backbone!
Differing P- and S-wave attenuation trends are a possible indicator of fracture connectivity
Wave propagation effects: Oscillatory test vs transmission experiment

Numerical upscaling based on Biot’s quasi-static equations (QS)

\[ u_z = -\Delta u e^{i\omega t} \]

Wave propagation modelling based on Biot’s dynamic equations (WP)

Pressure diffusion:
- FB-WIFF
- FF-WIFF

Domain size: 2 - 5 wavelengths (20 correlation lengths of the medium)
Attenuation and velocity estimation

Frequency [Hz]

10
2
10
3
10
4
10
5

Attenuation (1/Q)

0
0.02
0.04
0.06
0.08
0.1
0.12

Attenuation correction

QS:fracture
WP:fracture
WP:three layer
Qs:fracture + transmission

P-wave velocity [m/s]

3800
3900
4000
4100
4200
4300
4400
4500

Velocity correction

QS:fracture
QS:three layer
WP:three layer
WP:fracture

a) 

b) 

\[ Q_p^{-1}(\omega) = Q_{transmission}^{-1}(\omega) + Q_{scattering}^{-1}(\omega) + Q_{intrinsic}^{-1}(\omega) \]
Full-waveform sonic log measurements – Grimsel Felslabor (INJ2)

\[ Q_p^{-1}(\omega) = Q_{\text{spreading}}^{-1}(\omega) + Q_{\text{intrinsic}}^{-1}(\omega) + Q_{\text{transmission}}^{-1}(\omega) \]
Transmission coefficients and fracture compliance

+ Velocities → Transmission coefficient
→ Fracture compliance

Receiver 1
Incident wave
Fracture
Transmitted wave
Receiver 2

Graphs showing transmission coefficient and normal compliance vs. Abs(T) and Re(Z_N) [m/Pa].
Seismic attenuation in porous rocks containing stochastic fracture networks: Jürg Hunziker, Marco Favino, Eva Caspari, Beatriz Quintal, J. Germán Rubino, Rolf Krause and Klaus Holliger

Attenuation in fluid-saturated fractured porous media – quasi-static numerical upscaling vs dynamic wave propagation modeling: Eva Caspari, Mikhail Novikov, Vadim Lisitsa, Nicolás D. Barbosa, Beatriz Quintal, J. Germán Rubino and Klaus Holliger

Seismic transmissivity of fractures from full-waveform sonic log measurements: Nicolás D. Barbosa, Eva Caspari, J. Germán Rubino, Tobias Zahner, Andrew Greenwood, Ludovic Baron, Klaus Holliger

Efficient Finite Element Simulation Methods for Fracture Networks: Marco Favino, Jürg Hunziker, Klaus Holliger, Rolf Krause

Towards fracture characterization using tube waves: Jürg Hunziker, Shohei Minato, Eva Caspari, Andrew Greenwood and Klaus Holliger

Characterization and imaging of a fractured crystalline hydrothermal fault zone from hydrophone VSP data: A. Greenwood, E. Caspari, J. Hunziker, L. Baron, and K. Holliger.

Geophysical characterization of a hydrothermally active fault zone in crystalline rocks – GDP 1 borehole, Grimsel Pass: Eva Caspari, Ludovic Baron, Tobias Zahner, Andrew Greenwood, Enea Toschini, Daniel Egli and Klaus Holliger

A numerical approach for studying attenuation in interconnected fractures: Beatriz Quintal, Eva Caspari, Klaus Holliger and Holger Steeb
Acknowledgements

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Numerical upscaling

Biot’s (1941) quasi-static poroelastic equations:

\[ \nabla \cdot \sigma = 0, \quad i \omega \frac{\eta}{k} w = -\nabla p \]

\[ \sigma = \left[ (H - 2G) \nabla \cdot u + \alpha M \nabla \cdot w \right] \mathbf{I} + G \left[ \nabla u + (\nabla u)^T \right], \]

\[ -p = \alpha M \nabla \cdot u + M \nabla \cdot w \]

Compression test:

\[ u_z = -\Delta u \, e^{i \omega t} \]

Simple shear test:

\[ H(\omega) = \frac{\langle \sigma_{zz}(\omega) \rangle}{\langle \varepsilon_{zz}(\omega) \rangle} \]

\[ Q_p^{-1}(\omega) = \frac{\Im(H(\omega))}{\Re(H(\omega))} \]

\[ G(\omega) = \frac{\langle \sigma_{xz}(\omega) \rangle}{\langle 2 \varepsilon_{xz}(\omega) \rangle} \]

\[ Q_s^{-1}(\omega) = \frac{\Im(G(\omega))}{\Re(G(\omega))} \]
2D Wave propagation transmission experiment (time domain)

Biot’s (1962) **dynamic** poroelastic equations (after Masson and Pride, 2010)

\[
\nabla \cdot \sigma = \rho \frac{\partial v}{\partial t} + \rho_f \frac{\partial q}{\partial t}
\]

\[
\rho_f \frac{T}{\phi} \frac{\partial q}{\partial t} + \rho_f \frac{\partial v}{\partial t} + \frac{\eta}{k_0} q = -\nabla p
\]

\[
-\frac{\partial p}{\partial t} = M (\alpha \nabla \cdot v + \nabla \cdot q) + s_f,
\]

\[
\frac{\partial \sigma}{\partial t} = (\lambda_u \nabla \cdot v + \alpha M \nabla \cdot q) I + \mu \left[ \nabla v + (\nabla v)^T \right] + s.
\]

Wave propagation transmission experiment:

Steady limit of permeability: Neglects viscous boundary layers!

\[
\frac{\eta}{k_0}
\]

Domain size: 2 - 5 wavelengths (20 correlation lengths of the medium)

Attenuation: spectral-ratio type method
Fractured medium

**Background:** stiff porous matrix of low porosity and permeability

**Fractures:** compliant inclusion of high porosity and permeability

<table>
<thead>
<tr>
<th></th>
<th>Background</th>
<th>Fracture</th>
<th>Fluid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk modulus [Gpa]</td>
<td>34</td>
<td>0.025</td>
<td>2.4</td>
</tr>
<tr>
<td>Shear modulus [GPa]</td>
<td>32</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>Porosity</td>
<td>0.06</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Permeability [m²]</td>
<td>10^{-18}</td>
<td>10^{-11} (0.5 10^{-11} - 10^{-10})</td>
<td></td>
</tr>
</tbody>
</table>

**Fracture network parameter:** Power law length distribution

\[
n(l, L) = d_{frac} (a - 1) \frac{l^{-a}}{l_{min}^{-a+1}} \quad \text{for } l \in [l_{min}, l_{max}]
\]

<table>
<thead>
<tr>
<th></th>
<th>Constant</th>
<th>Variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exponent a</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Length (l_{min}, l_{max}) [mm]</td>
<td>10, 200</td>
<td>10, 200</td>
</tr>
<tr>
<td>Fracture volume (d_{frac}) [%]</td>
<td>1.5 – 3.25</td>
<td>12</td>
</tr>
<tr>
<td>Aperture [mm]</td>
<td>0.5</td>
<td>0.7 - 3</td>
</tr>
</tbody>
</table>
Constant aperture: P- and S-wave attenuation

Fracture-to-background flow is dominant for P-waves

Fracture-to-fracture flow is dominant for S-waves
Pressure fields

P-wave

S-wave

Fracture-to-fracture flow is dominant for S-waves

⇒ Larger induced pressure gradients

Fracture-to-background flow is dominant for P-waves

⇒ Larger remaining pressure gradients
Comparison constant vs. variable aperture: P-wave attenuation

Constant aperture

\[ \text{vol}_{\text{frac}} = 3.25 \% \]
\[ \text{con} = 210 \]

Variable aperture

\[ \text{vol}_{\text{frac}} = 12 \% \]
\[ \text{con} = 204 \]

→ Same degree of connectivity
→ Increase in fluid storage volume within fractures (larger apertures!)