Targeting horizontal stresses and optimal hydraulic fracturing locations through seismic data

David Gray
Senior Research Advisor
CGGVeritas
What matters in Hydraulic Fracturing?

- Fractures
  - Will they open?
  - Will they stay in zone?
  - How wide?
  - What type?
  - What direction?
  - Will they stay open?
What do we need?

- **Rock Strength**
  - Young’s modulus, Poisson’s ratio, Unconfined compressional strength

- **Stress**
  - Horizontal and Vertical stresses, $\sigma_{H_{\text{max}}}$, $\sigma_{h_{\text{min}}}$, $\sigma_{z}$
  - Closure stress $= \sigma_{h_{\text{min}}}$
  - Hoop stress $= \sigma_{\theta\theta}$ and Fracture Initiation Pressure
  - Stress state
What can we get from seismic?

- Rock Strength
  - Young’s modulus, Poisson’s ratio
- Stress
  - Vertical and horizontal stresses
  - Closure stress
  - Hoop stress
  - Stress state
How can we get these from seismic?

- **Rock Strength**
  - Young’s modulus, Poisson’s ratio
  - AVO/LMR (Amplitude Versus Offset / Lamé’s Moduli)
  - Multicomponent Seismic Analysis

- **Stress**
  - Azimuthal AVO, Azimuthal Velocities
  - Multicomponent Seismic Fracture Analysis
When can we get these from seismic?

- **Rock Strength – NOW!**
  - AVO (1982-present, 27 years)
  - LMR (1997-present, 12 years)
  - Joint and Simultaneous Inversion (~2004–present, ~5 years)
  - Multicomponent Analysis (~1980-present, ~30 years)
- **Stress – NOW!**
  - Azimuthal AVO (1996-present, 13 years)
  - Multicomponent Fracture Analysis (~1986-present, ~23 years)
  - Horizontal and Vertical Stresses (Now)
    - We’ll show you later
Rock Strength

Generating Rock Strength Values from Simultaneous or Joint Inversion of Seismic Data
Example from SE of Red Deer, AB
Rock Strength

Brinell Hardness Test

Hammer & Plate Seismic

http://www.kgs.ku.edu/Geophysics/OFR/2006/OFR06_01/index.html
Density – Simultaneous Inversion

Colorado Shale

2WS
Important according to Goodway (CSEG lunch, Feb. 09), it can serve as a proxy for differential stress
Lame’s Modulus \( (\lambda=\rho V_p^2-2\mu) \)

Colorado Shale

2WS
Poisson’s Ratio ($\nu$)

\[
\nu = \frac{\lambda}{2(\lambda + \mu)}
\]

\[
\sigma_x = \sigma_y = \sigma_z \frac{\nu}{1 - \nu}
\]
Young’s Modulus (E)

\[ E = 2\mu(1+\nu) \]

Brittleness
Rock Strength Conclusions

- Rock Strength derived from seismic since LMR in 1997
- Translate to values Engineering want
  - Young’s modulus
  - Poisson’s ratio
- Seismic measures “dynamic” rock strength
  - Calibrate to static values
    - Usually done with a scalar (e.g. 0.65)
    - Static closer to dynamic in older, harder rocks like these
Stress

Vertical, Maximum and Minimum Horizontal Stresses from Seismic Example from SE of Red Deer, AB
How do we get stress from seismic?

- Hooke’s Law \( \varepsilon_i = S_{ij} \sigma_j; \ i, j \in 1,2,\ldots,6 \)
  - Strain = Compliance \* Stress
- Isotropic Stress
  - \( \sigma_x = \sigma_y = \sigma_z \frac{\nu}{1 - \nu} \)
- We know \( \sigma_y > \sigma_x \), in general
  - Anisotropic stresses
    - \( \Rightarrow \) Anisotropic Compliance
How do we get stress from seismic?

- Hooke’s Law \( \varepsilon_i = S_{ij} \sigma_j; \ i, j \in 1, 2, ..., 6 \)
  - Strain = Seismic * Stress
- For a Horizontally Transverse Isotropic (HTI) medium
  - Linear Slip Theory \( \varepsilon_i = \{S_b + S_f\} \sigma_j \)

\[
S_b = \begin{bmatrix}
\frac{1}{E} & -\frac{v}{E} & -\frac{v}{E} \\
\frac{v}{E} & \frac{1}{E} & -\frac{v}{E} \\
\frac{v}{E} & \frac{v}{E} & \frac{1}{E}
\end{bmatrix}
\]

\[
S_f = \begin{bmatrix}
Z_N & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & Z_T & 0 \\
0 & 0 & 0 & 0 & Z_T
\end{bmatrix}
\]
How? - Horizontal Stresses and Seismic AzAVO

\[ \sigma_x = \sigma_z \frac{\nu(1 + \nu)}{1 + EZ_N - \nu^2} \]

\[ \sigma_y = \sigma_z \nu \left( \frac{1 + EZ_N + \nu}{1 + EZ_N - \nu^2} \right) \]

\[ \sigma_z = \sigma_v(z) = \int_0^Z g \rho(h) dh \]

- **Seismic AzAVO Terms**
  - \( E \) – Young’s Modulus
  - \( \nu \) – Poisson’s Ratio
  - \( Z_N \) – Normal Compliance

![Diagram of stress and strain relations](image)
How do we get stress from seismic?

- Hooke’s Law
  - Strain = Seismic * Stress
  - Movement = Seismic * Force
  - ΔMovement = Seismic * ΔForce
  - Fracture = Seismic * ΔPressure
Assumptions

Some assumptions have been made in order to produce these results. Many are due to the preliminary nature of this work and will be addressed in future work. The assumptions are:

1. Shear-wave background velocities for the inversions are estimated from the “Mudrock Line” of Castagna et al (1985).
2. Calibration of estimated stresses, assumed the WCSB Atlas stress measurements are valid for this area.
3. $M_{Z_N} \approx \mu Z_t$
4. Azimuthal anisotropy in the seismic is due to differential horizontal stresses.
5. Linear Slip theory and all its assumptions are valid for these rocks.
6. The rocks behave elastically.
Vertical Stress Gradient from $g^*\rho$

Colorado Shale
Vertical Stress

\[ \sigma_z \approx \Sigma_i [g^* \rho(i) * z(i)] \]
Calibrated Minimum Horizontal Stress

\[ \sigma_{hmin} = \sigma_x = K_x \sigma_z \]

Colorado Shale
Calibrated Maximum Horizontal Stress

\[ \sigma_{Hmax} = \sigma_y = K_y \sigma_z \]
σ_x (= Closure Stress) in 2WS

Note range varies from ~20 MPa - ~26 MPa over this 10 km² area.
Differential Horizontal Stress Ratio \( \text{DHSR} = \frac{\sigma_H - \sigma_h}{\sigma_H} \)

Estimates require only seismically derivable parameters as \( \sigma_z \) cancels.

\[
0.00 \leq \frac{\sigma_H - \sigma_h}{\sigma_H} = \frac{K_y - K_x}{K_y} \leq 0.05
\]
Stress State

What do these stress measurements tell us?
Example from SE of Red Deer, AB
### Stress variations with Depth (after Zoback)

<table>
<thead>
<tr>
<th>Condition</th>
<th>Movement Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_H &gt; \sigma_h &gt; \sigma_z$</td>
<td>Thrust = Horizontal fractures that move horizontally w/o much overburden allows them to go up</td>
</tr>
<tr>
<td>$\sigma_H &gt; \sigma_z &gt; \sigma_h$</td>
<td>Shear = Vertical fractures that move horizontally</td>
</tr>
<tr>
<td>$\sigma_z &gt; \sigma_H &gt; \sigma_h$</td>
<td>Normal = vertical fractures that move vertically</td>
</tr>
</tbody>
</table>

**Direction of Movement**

- Thrust = Horizontal fractures
- Shear = Vertical fractures
- Normal = Vertical fractures

**Normal to Fractures**

- Thrust = Horizontal fractures
- Shear = Vertical fractures
- Normal = Vertical fractures
Stress and Fractures

- If $\sigma_{Hmax} \approx \sigma_{hmin}$
  - Tensile cracks any direction
  - $\parallel$ rock weakness
  - Fracture network

- If $\sigma_{Hmax} >> \sigma_{hmin}$ (>5%)
  - Fractures $\parallel \sigma_{Hmax}$
  - Shear Fractures
  - Tensile Fractures
  - Connect to existing fracture network for production

$\sigma_{hmin} = \text{Closure Stress}$
Pressure

$\sigma_{Hmax}$
DHSR with Orientation on Young’s Modulus
Hydraulic fracture swarms where rocks are brittle ($E > 17$ GPa) and stress ratio is small ($DHSR < 6\%$).
Good and bad areas for Hydraulic Fracs in the Colorado

Areas in green indicate zones where hydraulic fractures will be optimal. In yellow, where aligned fractures are more likely to occur. In red, where hydraulic fracturing won’t work because the rock is too ductile.
Differential Horizontal Stress Ratio \( (\sigma_H - \sigma_h)/\sigma_H \)

Colorado Shale

2WS
Good and bad areas for Hydraulic Fracs in the Colorado

Areas in green indicate zones where hydraulic fractures will be optimal. In yellow, where aligned fractures are more likely to occur. In red, where hydraulic fracturing won’t work because the rock is too ductile.
Young’s Modulus (E)

Colorado Shale

2WS
Probable zones of better Hydraulic Fractures in the 2WS Median

Map of 2\textsuperscript{nd} White Speckled Shale showing zones highlighted in seismic attribute crossplot. Green is where fracture swarms will form, red is where the rocks are more ductile and yellow is where aligned fractures will occur. Note that only about $\frac{1}{4}$ of this reservoir is optimal for hydraulic fracturing.
Differential Horizontal Stress Ratio Slice

Amplitude of SMS
with a window of 10 ms below
and showing the Arithmetic Mean.
Probable zones of better Hydraulic Fractures in the 2WS Median

Map of 2\textsuperscript{nd} White Speckled Shale showing zones highlighted in seismic attribute crossplot. Green is where fracture swarms will form, red is where the rocks are more ductile and yellow is where aligned fractures will occur. Note that only about \(\frac{1}{4}\) of this reservoir is optimal for hydraulic fracturing.
Young’s Modulus in 2WS
Fracture Initiation Pressure Vertical Borehole

\[ P_{FIS} \approx 3\sigma_{hmin} - \sigma_{Hmax} \]
Fracture Initiation Pressure Horizontal Borehole Side

\[ P_{FIS} \approx 3\sigma_{H_{\text{max}}} - \sigma_v \]

Colorado Shale
Fracture Initiation Pressure Horizontal Borehole Top

\[ P_{FIT} \approx 3\sigma_v - \sigma_{H\text{max}} \]

Colorado Shale
Conclusions

- What can we get from seismic?
  - Rock Strength
    - Young’s modulus, Poisson’s ratio
    - Dynamic needs to be calibrated to static
  - Stress
    - Vertical and Horizontal stresses, $\sigma_z, \sigma_{H_{\text{max}}}, \sigma_{h_{\text{min}}}$
    - Closure stress = $\sigma_{h_{\text{min}}}$
    - Hoop Stress, Fracture Initiation Pressure
    - Stress state
      - Better places for hydraulic fractures
      - Fracture type – vertical or horizontal
      - Fracture motion – vertical or horizontal

| $\sigma_H > \sigma_h > \sigma_v$ | Thrust = Horizontal fractures that move horizontally w/o much overburden allows them to go up |
| $\sigma_H > \sigma_v > \sigma_h$ | Shear = Vertical fractures that move horizontally |
| $\sigma_v > \sigma_H > \sigma_h$ | Normal = vertical fractures that move vertically |
Acknowledgements

- CGGVeritas, EnCana, Apache, Talisman, Magnitude, Fairborne
Targeting horizontal stresses and optimal hydraulic fracturing locations through seismic data

David Gray
Senior Research Advisor
CGGVeritas