Advanced seismic inversion for geomechanics applications in unconventional reservoirs

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Introduction

• Sensitivity of hydraulic fracturing to stress and natural fractures
• 3D Mechanical Earth Model
• Prestack seismic inversion
• Mechanical stratigraphy
• Geomechanical properties
• Pore pressure
• In-situ stress
• Conclusion
Sensitivity of hydraulic fractures to stress and fractures

Increasing horizontal stress anisotropy

Ref: Kresse et al., 2011, ARMA 11-363
The 3D Mechanical Earth Model

- Framework model
- Mechanical stratigraphy
- Elastic properties and strength parameters
- Earth stress and pore pressure

Geology

- Young's modulus, $E$, MPa
- Friction angle, $\phi$, degrees
- Poisson's ratio, $\nu$
- Unconfined compressive strength, UCS, MPa
Amplitude Variation with Offset (AVO)

AVO is the variation in the amplitude of a seismic reflection with offset (distance) between source and receiver.

The variation with $q$ allows the P-impedance, $I_P = \rho V_P$, S-impedance, $I_S = \rho V_S$, and $V_P / V_S = I_P / I_S$ to be determined.

Seismic inversion for unconventional reservoirs needs to take into account anisotropy:

- **Transverse isotropy**
  - Kimmeridge shale
  - Photo by John Cook
  - Schlumberger Cambridge Research
  - 37 μm

- **Orthotropic**
  - Marcellus shale
  - Engelder et al. (2009)
  - AAPG Bulletin, 93, 857–889

- **Monoclinic**
  - Utica shale
  - Photo by Bob Jacobi
  - http://blog.aapg.org/learn/?p=472
Mechanical stratigraphy

Mechanical stratigraphy

Rock Classes

Well placement impacts production!

Geomechanical properties


Static Young’s modulus and Poisson’s ratio predicted using the dynamic to static correlations (red) compared with core measurements (black dots).
Pore pressure

Pore pressure is difficult to measure in low permeability rocks, but has an important impact on drilling, hydrocarbon production and geomechanics applications such as hydraulic fracturing, etc.

For highest vertical resolution, use results of AVO inversion for pore pressure estimation.

In general, the relation between the AVO inversion results and pore pressure is lithology-dependent:

\[ P_p = P_p(\text{lithology}, I_p, V_p / V_s, \sigma_{ij}) \]
P-impedance between 3rd Bone Spring and Base Wolfcamp

![P-impedance between 3rd Bone Spring and Base Wolfcamp](image-url)
$V_p/V_S$ between 3rd Bone Spring and Base Wolfcamp
Pore pressure from acoustic and shear impedance

\[ P_p = P_p(\text{lithology, } I_p, \frac{V_p}{V_s}, \sigma_{ij}) \]
Pp gradient from acoustic and shear impedance

\[ P_p = P_p \text{ (lithology, } I_p, \frac{V_p}{V_s}, \sigma_{ij}) \]
Minimum Horizontal Stress

\[ \sigma_h = \alpha_h p + K_0 (\sigma_v - \alpha_v p) + \frac{E}{(1 - \nu^2)} (\varepsilon_h + \nu \varepsilon_H) \]
**Fracture Gradient**

\[
\sigma_h = \alpha_h p + K_0 \left( \sigma_v - \alpha_v p \right) + \frac{E}{(1 - \nu^2)} (\varepsilon_h + \nu \varepsilon_H)
\]
Seismic-based 3D Finite Element Model

Minimum horizontal stress

Shmin_AVO_2
Total stress [psi]

- 8500.00
- 7500.00
- 6500.00
- 5500.00
- 4500.00
- 3500.00
Seismic-based 3D Finite Element Model

Maximum horizontal stress
Seismic-based 3D Finite Element Model

Horizontal stress anisotropy
Effect of horizontal stress anisotropy on hydraulic fractures

Simulations of the same hydraulic fracture treatment with different horizontal stress anisotropy (minimum horizontal stress is constant).

Ref: Cohen et al. (2012) SPE 152541
Horn River example

Acoustic impedance

Shear impedance

Horn River example

Minimum horizontal stress from Finite Element Model

Horn River example

Instantaneous shut-in pressures (ISIPs) for a production pad in the Horn River Basin, with points color coded by ISIP from low (blue) to high (red).

Horn River example

Cumulative gas production for the southeast wells (blue) compared to northwest wells (red).

Horn River example

Direction of maximum horizontal stress from Finite Element Model

Conclusions

• In-situ stress and horizontal stress anisotropy are needed to model the propagation of hydraulic fractures
• Pore pressure has an important impact on drilling, hydrocarbon production and geomechanics applications
• Pore pressure, in-situ stress and horizontal stress anisotropy can be characterized using AVO inversion to build a predictive 3D mechanical Earth Model
• This enables optimization of well location, borehole trajectory, well spacing, and the design of hydraulic fractures, before the well is drilled