Rock physics and geophysics for unconventional resource, multi-component seismic, quantitative interpretation

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Topics

- Aspirational workflow
  - Google philosophy -- model based data reduction & Bayesian estimation
- New rock physics model (double critical for binary mixture)
- Relationship to cwave seismic reflectivity -- value of cwave
- Relationship to geomechanics -- the payoff
Inspiration

• Why vp-vs more robust than rho-vp or rho-vs?
• Statistical seismic attribute hunt for unconventional:
  – Young’s modulus, shear modulus, Poisson ratio, density
  – Density from converted wave (PS) seismic seemed key
• Critical point theory from statistical physics
  – Work by DeMartini et al. 2006
• Principle components approach of Saleh et al., SEG 1998
Quantitative Interpretation (QI) workflow for unconventionals

- Multi-component seismic imaging
- C-wave SSI w/ registration & uncertainty
- C-wave inversion (model based)
- Petrophysics (effective media)
- Wells
- Geology
- Stress and stratigraphy
- Geomech simulation
- Observed + uncertainty
- Predicted + uncertainty

- Model + σ
- "Trends"
- "Fuzzy bouncing beach balls (FB3)" & reservoir performance
- Microseismic analysis
- Verification
- Near surface velocity model
- Wavelet
- Markers
- Stress and stratigraphy
- Geomech parameters
- Near, far, PS stacks
- Horizons + velocity model
- Wavelet
- Velocity model
- Predicted + uncertainty
- Observed + uncertainty
Rock physics for unconventionals

\[ \xi = \text{geometry}; \text{e.g., ductile fraction, sorting } \sim f_d \]

\[ \zeta = \text{composition}; \text{e.g., compaction, diagenesis } \sim 1 - \exp(-E/E_0) \]

\[ R^{(0)} = \text{full PP stack} \]
\[ \text{SNR } \sim \mathcal{O}(\theta_0^0) > 0 \text{ dB for } \theta_m = 30^\circ \]

\[ R^{(1)} = \text{“full” PS stack} \]
\[ \text{SNR } \sim \mathcal{O}(\theta_0^2) > 8 \text{ dB} \]

\[ R^{(2)} = \text{“grad” PP stack, AVO} \]
\[ \text{SNR } \sim \mathcal{O}(\theta_0^4) > 25 \text{ dB} \]
Rock physics is 2D

\[ \tilde{v}_p = \frac{v_p - \min(v_p)}{\max(v_p) - \min(v_p)} \]
\[ \tilde{v}_s = \frac{v_s - \min(v_s)}{\max(v_s) - \min(v_s)} \]
\[ \tilde{\rho} = \frac{\rho - \min(\rho)}{\max(\rho) - \min(\rho)} \]

\[ v_p = (8000 \text{ ft/s}, 18000 \text{ ft/s}) \]
\[ \rho = (2.1 \text{ gm/cc}, 2.8 \text{ gm/cc}) \]
\[ v_s = (3800 \text{ ft/s}, 11000 \text{ ft/s}) \]
New rock physics, links geophysics to geomechanics

Clay content is low (samples corresponding to Barnett Light in Figure 4), slip is expected to be unstable ($a - b < 0$) on the small faults surrounding the hydraulic fractures producing numerous microearthquakes. Where clay content is high (Barnett Dark in Figure 4) slip on faults is expected to be stable ($a - b > 0$), resulting in relatively few microearthquakes in these regions. As explained in the next section, even when ($a - b < 0$) and fault slip is expected to be unstable, other factors affect whether slip is stable or not (Ikari et al., 2011). One critical factor is the orientation of a given fault with respect to the prevailing stress field.

Figure 4: Variation of fault friction (black circles) and the stability parameter ($a - b$) (red squares) as a function of clay plus organic content in shale gas reservoir samples. Black bars show errors for values of ($a - b$). The specific reservoir for each sample is denoted by the labels above the datapoints. Note the transition from stable to unstable sliding at around 30% clay plus organic content.

Slow Slip on Mis-oriented Faults

In fractured rock masses there are pre-existing fractures and faults at a variety of orientations. Some of these faults are likely to be well-oriented for slip in the ambient stress field, which are sometimes termed critically-stressed faults (Zoback, 2007). While faults that are mis-oriented for slip in the ambient stress field would normally not be expected to be capable of slipping, however, the strong elevation of fluid pressure during hydraulic fracturing is capable of triggering slip on mis-oriented faults. In this section, we demonstrate that induced slip on mis-oriented faults is expected to be slow slip, undetected in micro-seismic surveys. We argue below that slow slip on faults is likely to be a fundamental component of hydraulic stimulation.

The left side of Figure 6 shows an estimate of the minimum pore pressure perturbation induced in the reservoir during hydraulic fracturing of the five wells shown in Figure 5. Vermylen and Zoback (2011) showed that the rapid pressurization that accompanied the simultaneous fracturing of wells A and B caused a large, poroelastic change in the least principal stress that increased with stage number and was most notable close to the heel areas of the wells. The largest poroelastic stress changes were observed in wells A and B because the frac stages were carried out in much less time than in the other wells. For example, wells A and B were fractured in 100 hours, whereas it took twice as long hydraulically fracture wells D and E, even though there were the same number of stages, rates and amounts of fluid, etc. Vermylen and Zoback (2011) interpreted the increase of the least principal stress as a poroelastic effect because the effect was largest when the fluid pressure had the least amount of time to dissipate between hydraulic fracturing stages. As the pore pressure change that caused the stress change must be at least as large as the observed stress change, the values shown in the figure represent a lower bound estimate of the pore pressure change experienced by the reservoir during the multiple hydraulic fracturing stages in each well. The right side of Figure 6 shows...
Double critical rock physics model

fundamental regressed form:

\[ v_p = A_{vp} + B_{vp} \zeta + C_{vp} \xi \pm \sigma_{vp} \]
\[ \rho = A_{\rho} + B_{\rho} v_p + C_{\rho} \xi \pm \sigma_{\rho} \]
\[ v_s = A_{vs} + B_{vs} v_p \pm \sigma_{vs} \]

double critical form (critical exponents) using \( \rho \equiv \phi \rho_f + (1 - \phi) \rho_s \)

\[ \phi = \phi_c - \frac{\phi_c}{n_\zeta} \zeta - \frac{\phi_c}{n_\xi} \xi \]

to more explicitly see the critical scaling (two order parameters, from binary mixture)

\[ \zeta \sim \left( \frac{\phi_c - \phi}{\phi_c} \right)^{n_\zeta} \quad \xi \sim \left( \frac{\phi_c - \phi}{\phi_c} \right)^{n_\xi} \quad \phi_c \approx 42\% \quad n_\zeta \approx 2 \]

ductile coordination number  
brittle coordination number  
\[ = \text{capture fraction} = \frac{n_\xi - n_\zeta}{n_\xi} \]
\[ = 36\% \text{ for uncompacted sandstones (small & large grains)} \]
\[ = 92\% \text{ for compacted unconventional (ductile & brittle grains)} \]

unconventionals range from organic rich shale, to siltstone, to marl, to sandstone, to limestone
Cwave seismic reflection coefficient approximation

small contrast (Born approximation), expanded in small angle for convenience (not needed)

\[ R_{PP} = \frac{1}{2} \left( \frac{\Delta \rho}{\rho} + \frac{\Delta v_p}{v_p} \right) + \left( -2 r_{sp}^2 \frac{\Delta \rho}{\rho} + \frac{1}{2} \frac{\Delta v_p}{v_p} - 4 r_{sp}^2 \frac{\Delta v_s}{v_s} \right) \theta^2 + \left( \frac{2}{3} r_{sp}^2 \frac{\Delta \rho}{\rho} + \frac{1}{3} \frac{\Delta v_p}{v_p} + \frac{4}{3} r_{sp}^2 \frac{\Delta v_s}{v_s} \right) \theta^4 + \mathcal{O}(\theta^6). \]

\[ R_{PS} = \left[ \left( \frac{1}{2} - r_{sp} \right) \frac{\Delta \rho}{\rho} - 2 r_{sp} \frac{\Delta v_s}{v_s} \right] \theta + \left[ \left( \frac{1}{12} + \frac{2}{3} R_{sp} + \frac{3}{4} r_{sp}^2 \right) \frac{\Delta \rho}{\rho} + \left( \frac{4}{3} r_{sp} + 2 r_{sp}^2 \right) \frac{\Delta v_s}{v_s} \right] \theta^3 + \mathcal{O}(\theta^5) \]

where \( r_{sp} \equiv \frac{v_s}{v_p} \)

write in the composite linear form:

\[ R = M_\theta M_A M_{RP} \Delta r \]

where

\[
R = \begin{pmatrix} R_{PP}(\theta = 0) \\ \vdots \\ R_{PP}(\theta_m) \\ R_{PS}(\theta = 0) \\ \vdots \\ R_{PS}(\theta_m) \end{pmatrix}, \quad \Delta r \equiv \begin{pmatrix} d\zeta \\ d\xi \end{pmatrix}, \quad \Delta r \equiv \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & (\Delta \theta)^2 & 0 & (\Delta \theta)^4 \\ 0 & (\Delta \theta)^2 & 0 & (\Delta \theta)^4 \\ 0 & 0 & (\Delta \theta)^2 & 0 & (\Delta \theta)^4 \\ 0 & 0 & 0 & (\Delta \theta)^2 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & (N-2) \Delta \theta & 0 & 0 & 0 \end{pmatrix}, \quad M_{\theta} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & (\Delta \theta)^2 & 0 & 0 \\ 0 & (\Delta \theta)^2 & 0 & 0 & 0 \\ 0 & 0 & 0 & (\Delta \theta)^2 & 0 \\ 0 & 0 & 0 & 0 & (\Delta \theta)^2 \end{pmatrix}, \quad M_{A} = \begin{pmatrix} -\frac{1}{2} & 0 & \frac{1}{2} & 0 & 0 \\ -r_{sp} & -2 |r_{sp}|^2 & 0 & r_{sp} \frac{1 + r_{sp}}{2} & r_{sp} \frac{1 + r_{sp}}{2} \end{pmatrix}, \quad M_{RP} = \begin{pmatrix} B_{\rho} B_{v_p} C_{v_p} & B_{v_p} \frac{C_{v_p}^p}{v_p} & B_{v_p} \frac{C_{v_p}^p}{v_p} \\ B_{v_p} \frac{C_{v_p}^p}{v_p} & B_{v_p} \frac{C_{v_p}^p}{v_p} & B_{v_p} \frac{C_{v_p}^p}{v_p} \end{pmatrix}
\]
SVD analysis

make two SVDs:

\[
M_\theta = U_1 \Sigma_1 V_1^T \quad \Sigma_1 V_1^T M_{AMRP} = U_2 \Sigma_2 V_2^T
\]

so that weighted stacks are given by:

\[
\begin{bmatrix}
R_0 \\
R_1 \\
R_2 \\
\vdots
\end{bmatrix}
\equiv U_1^T R = U_2^T \Sigma_2 V_2^T \begin{pmatrix} d\zeta \\ d\xi \end{pmatrix}
\]

stack weightings

PC of RP

weighted stacks to RP

SNR of weighted stacks

\[
\Sigma_1 \equiv \begin{pmatrix}
\lambda_0 & 0 & 0 & \cdots \\
0 & \lambda_1 & 0 & \cdots \\
0 & 0 & \lambda_2 & \cdots \\
\vdots & \vdots & \vdots & \ddots
\end{pmatrix}
\]
Structure of the SVD

\[ \tilde{\zeta} \text{ composition} \]

\[ \tilde{\xi} \text{ geometry} \]

(a) \[ R_5(PS) \]
\[ R_4(PP) \]
\[ R_3(PS) \]
\[ R_2(PP) \]
\[ R_1(PS) \]
\[ R_0(PP) \]

(b) \[ V_2^T \]

\[ \tilde{\zeta} \text{ composition} \]

\[ \theta_m = 30^\circ \]

\[ \Delta \rho/\rho \]
\[ r_{ps}^2 \Delta \nu \]
\[ \Delta r_{ps}/r_{ps} \]
\[ \Delta E/E \]
\[ \Delta G/G \]
\[ \Delta K/K \]

(a) \[ \tilde{\zeta} \text{ composition} \]

\[ \Delta \rho/\rho \]
\[ r_{ps}^2 \Delta \nu \]
\[ \Delta r_{ps}/r_{ps} \]
\[ \Delta E/E \]
\[ \Delta G/G \]
\[ \Delta K/K \]

(b) \[ \tilde{\xi} \text{ geometry} \]

\[ V_2^T \]

\[ U_2^T \]
cwave (PS) is needed to predict fracturing, and is better than AVO!!
Geomechanical connection to microseismic

- fracture interaction
- fluid flow within fractures
- dynamic friction of fractures
- fracture tip propagation

behavior is determined by balance between 5 physics
Value of adding cwave and microseismic to estimation of fracability!

Google search results:
1. microseismic & cwave (98%)
2. cwave (50%)
3. AVO (30%)
4. conventional seismic (25%)
5. geology alone (5%)