# Lithological Controls on Mechanical Anisotropy in Shales to Predict In Situ Stress Magnitudes and Potential for Shearing of Laminations during Fracturing*

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## Abstract

Accurate and repeatable assessments of in situ stress magnitudes and orientation in unconventional reservoirs can be complicated by the heterogeneous, inelastic, and/or anisotropic mechanical properties of these rocks. The associated vertical and lateral variation in pore pressure and stress through the target zones and bounding intervals can further complicate this effort. For these reasons, some additional factors need to be considered beyond the typical workflow of determining stress state from mini-frac type data and using this data to calibrate log derived stress profiles. We present some case study examples from hydrocarbon-producing shales where a more rigorous analysis of the injection test data and of the shale mechanical properties has allowed a more accurate and repeatable assessment of in situ stress and potential for lamination shearing. Horizontal fracture growth through shear activation of bedding-parallel fabric can be a preferred fracture propagation mechanism in these shales and this behavior can be diagnosed by this improved workflow. In one case study example, in the tight gas Montney siltstone of Western Canada, shear strength anisotropy is shown to be very significant, with bedding parallel shear cohesion less than 10% of the bulk rock cohesion. It is shown through theory and through pressure transient analysis of case study minifrac injection data that shearing of laminations can be predicted, diagnosed and minimised during hydraulic fracturing stimulation. This shear fracturing mechanism is also stress dependent and its understanding requires assessment of all in situ stress magnitudes, not just minimum horizontal stress. An improved method of determining these stress magnitudes is described through multi-component acoustic measurements in core samples. In this way, a petrophysical relationship can be established between anisotropy parameters and rock properties.

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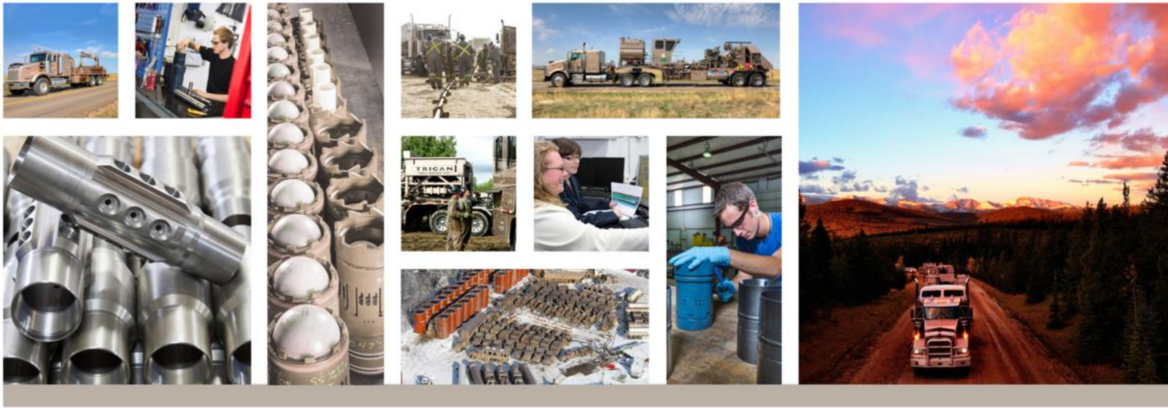


# Lithological Controls on Anisotropy in Shales to Predict In Situ Stress Magnitudes and Potential for Shearing of Laminations During Hydraulic Fracturing

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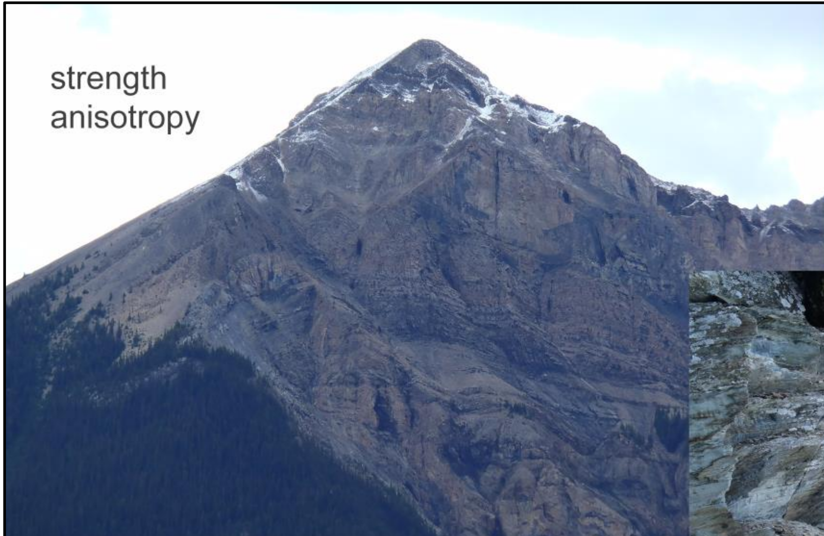
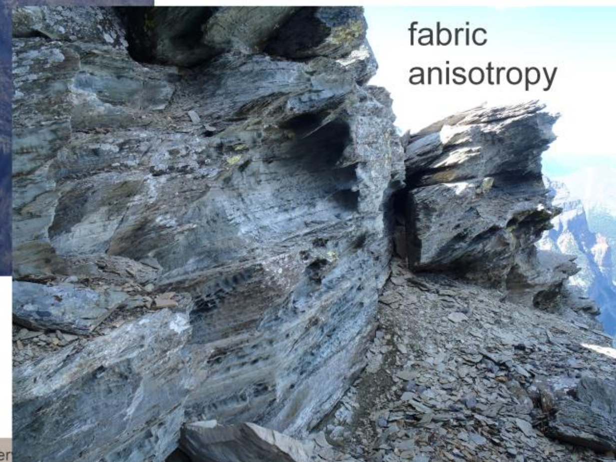


# Outline

Lithological Controls on Anisotropy in Shales to Predict In Situ Stress Magnitudes and Potential for Shearing of Laminations During Hydraulic Fracturing

- Reason for topic
- Anisotropy in Shales
  - Directional dependence of properties: stiffness, strength, flow
- Lithological Controls
  - Can lithology predict this?
- Implications and applications: stress magnitudes, lamination shearing
- Summary
- Questions

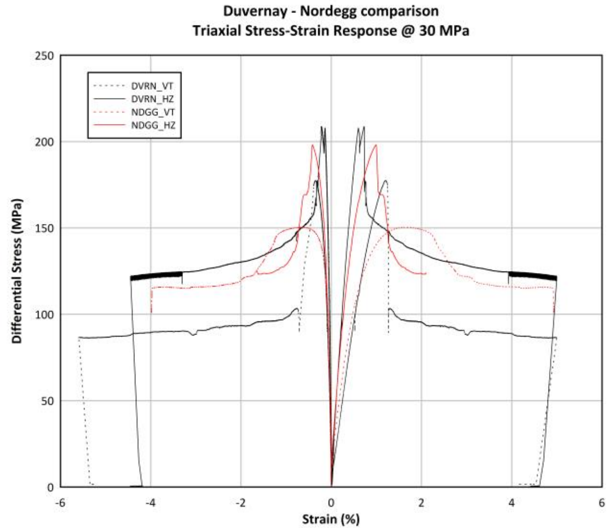
# Reason for Topic

Observations:

- Anisotropy perceived as having $2^{nd}$ order importance, not always true
- Elastic anisotropy
  - Cost to obtain data, uncertain ROI
  - Mechanical data not often used beyond log calibration for frac model
- Minimal elastic anisotropy and significant strength anisotropy can coexist
- Strength anisotropy
  - A spectrum from laminated bedding to PSF
  - Below log resolution
  - Weakest zone is most important, obscured by averaging methods
- Lithology is well understood, how can we use it to improve concept of anisotropy

# Anisotropy: Measurement

Triaxial testing of core for elastic properties and strength



# Elastic Anisotropy: Dynamic Data

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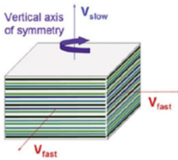
$\sigma_i = C_{ij}\varepsilon_j$ Stress related to strain through a stiffness tensor




Jenner, 2011 CSEG

$C_{11}, C_{33}, C_{44}, C_{66}, C_{13}$ 5 unique stiffness parameters for VTI anisotropy

$C_{11} = \rho V_{p(x,y)}^2$ Vp in x-y plane (hz core), hz Stoneley

$C_{33} = \rho V_{p(z)}^2$ Vp in z-axis, or DTC

$C_{44} = \rho V_{sv(x,y)}^2$ Vs in z-x or z-y plane, DTS

$C_{66} = \rho V_{sh(x,y)}^2$ Vs in x-y plane, Stoneley if $\delta < 0.2$

$$C_{13} = -C_{44} + \sqrt{\left(4\rho V_{p(45)}^2 - 2\rho V_{p(45)}^2 [C_{11} + C_{33} - 2C_{44}]\right) + (C_{11} + C_{44})(C_{33} + C_{44})}$$

$C_{13}$ requires Vp propagated 45 degrees to x-y plane…core plugs

Both VTI and HTI models require Vp oblique to symmetry

# Elastic Anisotropy: Data Calibration

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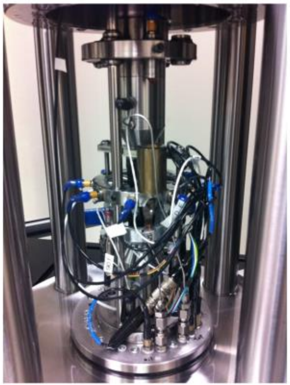
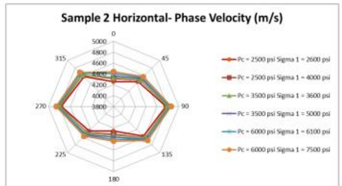
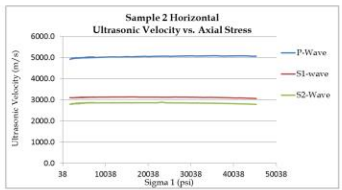
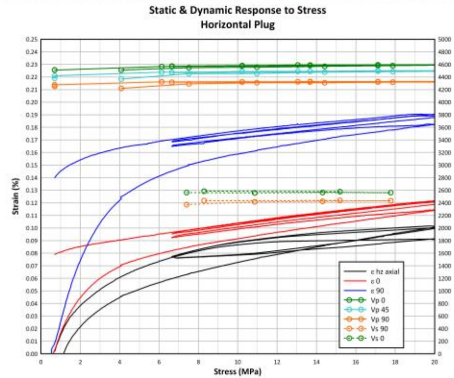
Static-Dynamic log-core calibration for VTI:

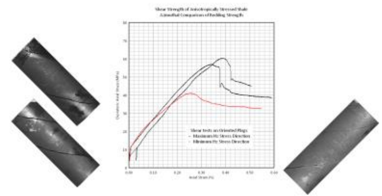
- Oriented core plugs with multi-axis acoustics
- All 5 Cij parameters possible in a hz plug
- Simultaneous static-dynamic measurements







Presenter’s notes: Properties vary vertically in fine scale layers and/or, preferred orientation of clay minerals.

# Anisotropy: Implications for Stress Estimates

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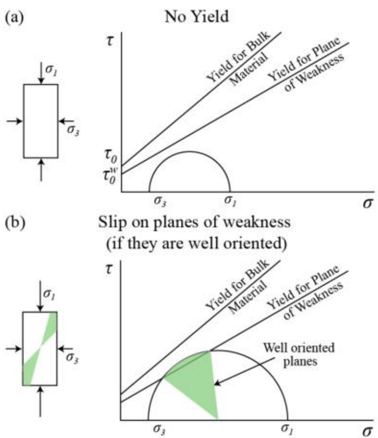
- "weak planes", etc mean caution required using elastic models
- Stress estimates using calibrated elastic models for VTI anisotropy:
  - Minimum horizontal stress

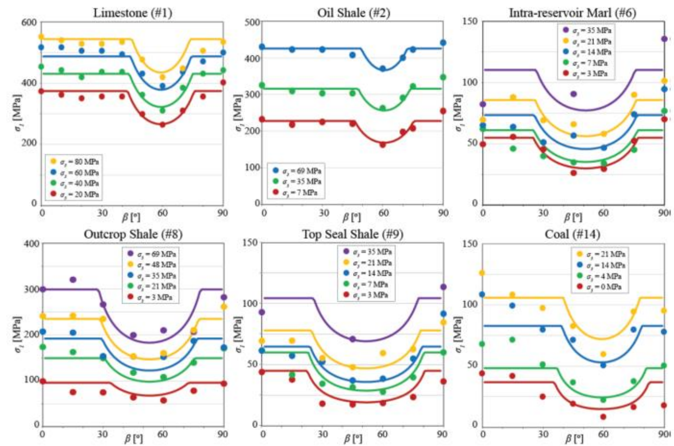
$$\sigma'_h = \underbrace{\frac{E_h}{E_v}\frac{v_v}{1 - v_h}}_{K_0}\sigma'_v + \text{strain terms}$$

Thiercelin and Plumb, 1994

# Strength Anisotropy

Rock is inherently weak along laminations, so strength may depend on position of laminae with respect to stress




Crawford, ARMA 12-290

# Strength Anisotropy: Measurement

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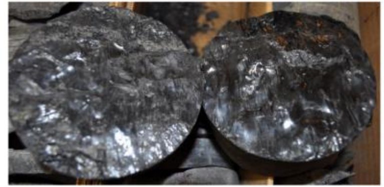
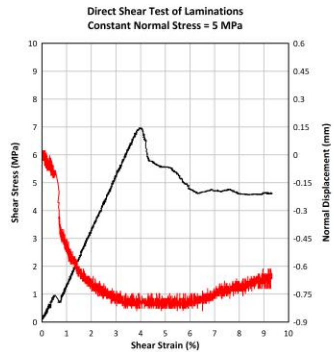





PSF

No shear cohesion

Weak laminae

Shear cohesion

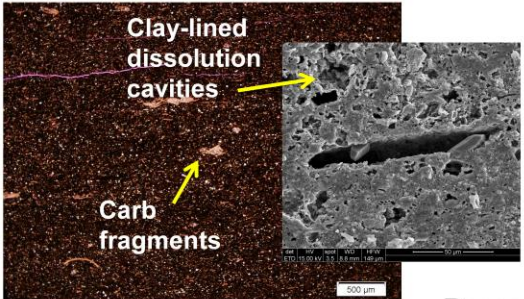
Dilatant failure

Shear strength measurement of specific laminations using direct shear testing.

Shear dilation is observed.

# Anisotropy in Shales

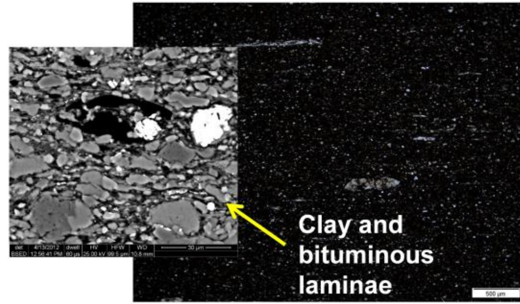
Duvernay: Examples of laminations defined by clays & organics




| Mnlgy | Wt% | | Mech. Aniso | |
|---|---|---|---|---|
| Qtz | 42 | | Eh/Ev | 2.1 |
| Carb | 48 | | SAR | 1.2 |
| Clay | 15 | | | |

Presence of clay increases anisotropy

Presence of carbonate cement decreases anisotropy




| Mnlgy | Wt% | | Mech. Aniso | |
|---|---|---|---|---|
| Qtz | 16 | | Eh/Ev | 1.7 |
| Carb | 62 | | SAR | 1.2 |
| Clay | 22 | | | |

# Anisotropy in Shales

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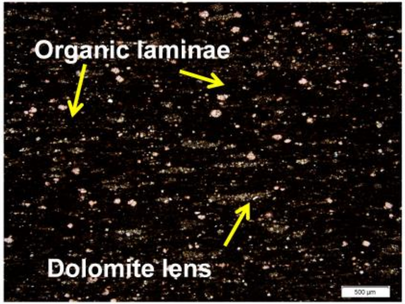
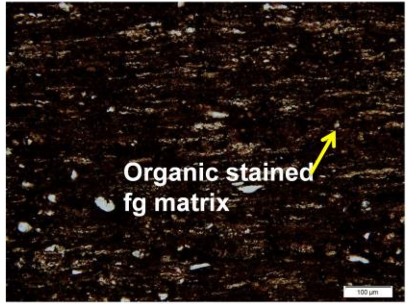
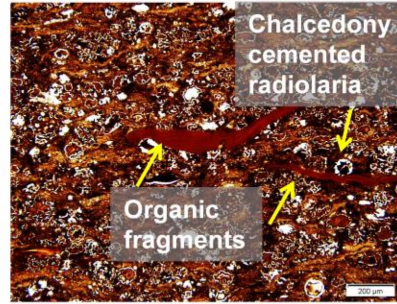
## Nordegg: Examples of laminations defined by carbonate & organics




| Mnlgy | Wt% | | Mech. Aniso | |
|---|---|---|---|---|
| Qtz | 17 | | Eh/Ev | 1.3 |
| Carb | 59 | | SAR | 1.5 |
| Clay | 6 | | | |
| TOC | 9 | | | |




| Mnlgy | Wt% | | Mech. Aniso | |
|---|---|---|---|---|
| Qtz | 44 | | Eh/Ev | 1.4 |
| Carb | 49 | | SAR | 1.2 |
| Clay | 4 | | | |
| TOC | 6 | | | |




| Mnlgy | Wt% | | Mech. Aniso | |
|---|---|---|---|---|
| Qtz | 81 | | Eh/Ev | 1.0 |
| Carb | 6 | | SAR | 1.0 |
| Clay | 8 | | | |
| TOC | 13 | | | |



Presenter's notes: Ante Creek example:

- Left: NDGG 6-9 2037m 40x ppl sparse biomicrite/bioclastic dolowackestone. Laminations defined by elongated dolomite lenses and thin, opaque o.m. lenses.
- Mid: NDGG 6-9 2034m 200x ppl sparse biomicrite/wackestone, ellipsoidal authigenic qtz cement along algal laminae
- Right: NDGG 6-9 2033m 100x ppl overexposed, large organic fragments and wavy algal laminae

# Anisotropy in Shales

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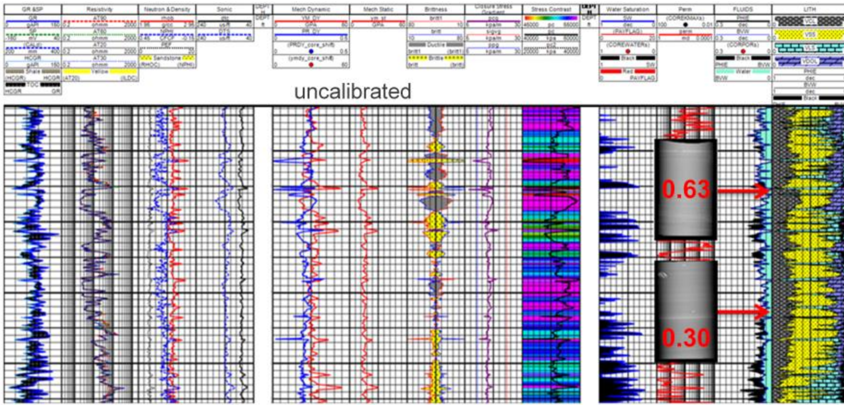


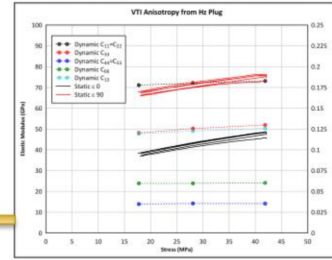


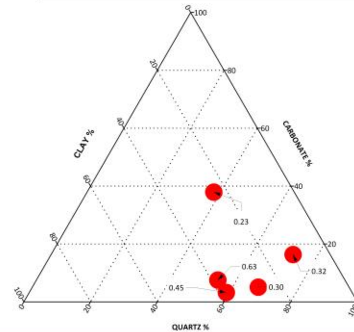


Elastic anisotropy related to mineralogy when clay ≥ 25%

Showing mineralogy and $K_0 = \dfrac{E_h}{E_v}\dfrac{v_v}{1-v_h}$

# Strength Anisotropy: Montney example

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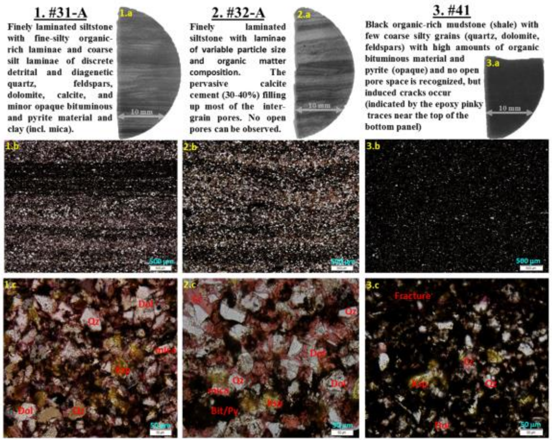
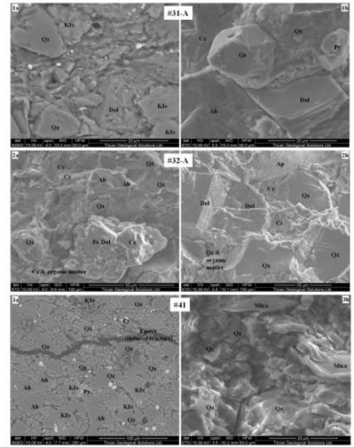
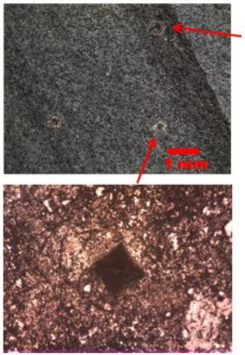



SPE 168730

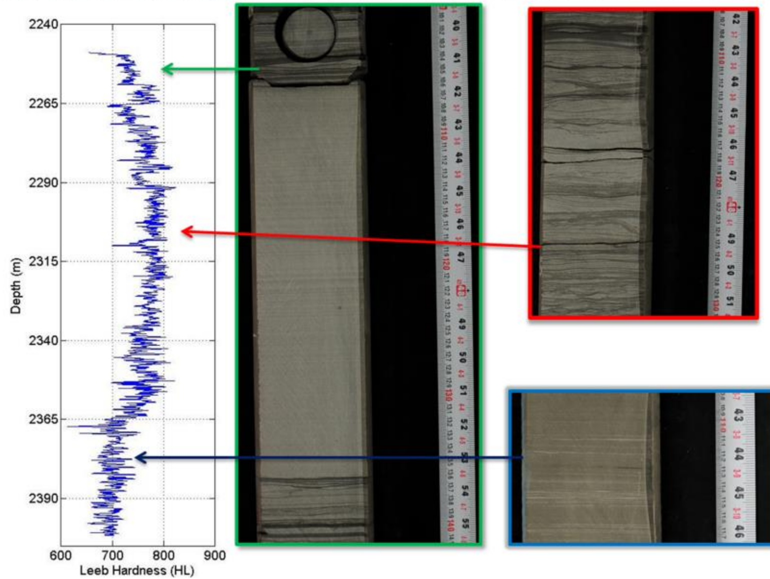
Laminae & clay structure suggest strength anisotropy

# Strength Anisotropy: Montney example

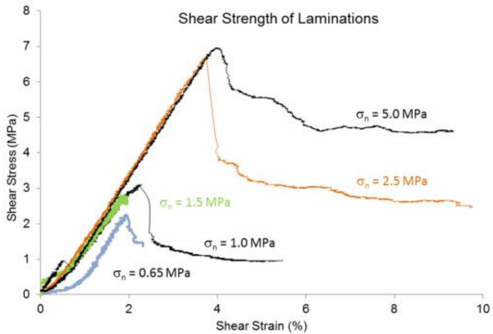



High resolution profiling by indentation or scratch testing identifies weak planes.

A range of shear strengths for each lithology.

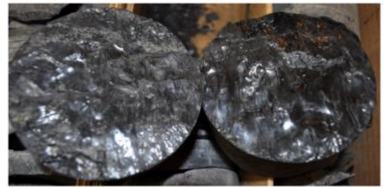


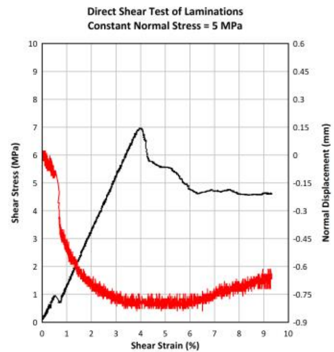
# Strength Anisotropy: Montney example




Shear strength measurement of specific laminations using direct shear testing.

Shear dilation is observed.






PSF

No shear cohesion

Weak laminae

Shear cohesion

Dilatant failure

# Strength Anisotropy: Montney example

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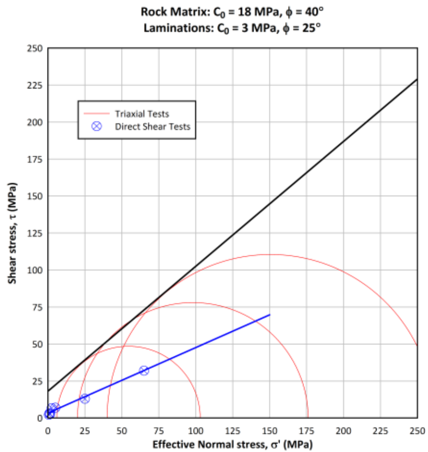
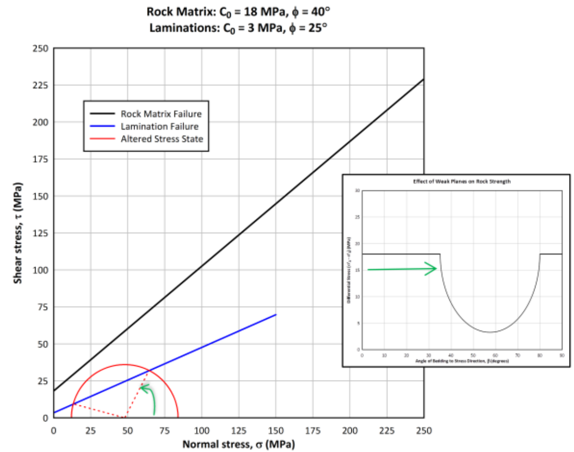



**Linear** failure criteria for rock matrix and laminations.
*Matrix contains laminations.




NWB stress concentration for MNTN in this area favors lamination shearing at some orientations.

# Anisotropy: Implications for Stress Estimates

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- "weak planes", etc mean caution required using elastic models
- Stress estimates using calibrated elastic models for VTI anisotropy:
  - Minimum horizontal stress

$$\sigma'_h = \frac{E_h}{E_v}\frac{v_v}{1-v_h}\sigma'_v + \frac{E_h}{1-{v_h}^2}\varepsilon_h + \frac{v_h E_h}{1-{v_h}^2}\varepsilon_H$$

Thiercelin and Plumb, 1994

$K_0$

  - Near-wellbore stress for isotropic case

$$\sigma'_{\theta(90°)} = 3\sigma'_{min} - 3\sigma'_{max} - \Delta p_w$$

Kirsch, 1898

  - NWB stress concentration for anisotropic

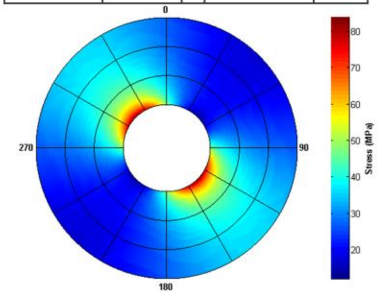
$$\sigma'_\theta = A\sigma'_{\theta, A} + B\sigma'_{\theta, B} + C\sigma'_{\theta, pw}$$

Jaeger and Cook, 2007

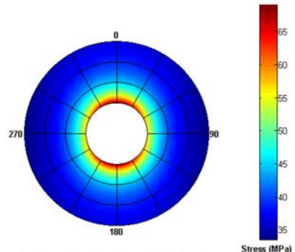
# Strength Anisotropy: Implications for Fracturing

- Near wellbore stress examples using isotropic elastic models

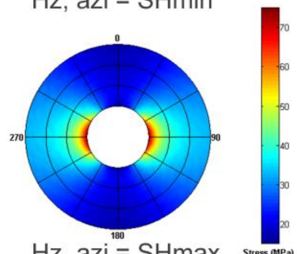
| Stress | MPa | | Well Cond-ns | |
|---|---|---|---|---|
| SHmin | 57 | | Pp grad | 14 |
| SHmax | 75 | | Mud grad | 14 |
| Sv | 72 | | | |



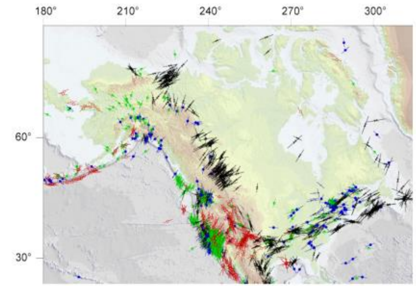

Vertical well

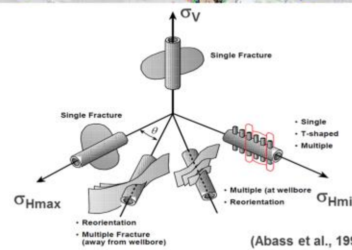



Hz, azi = SHmin




Hz, azi = SHmax



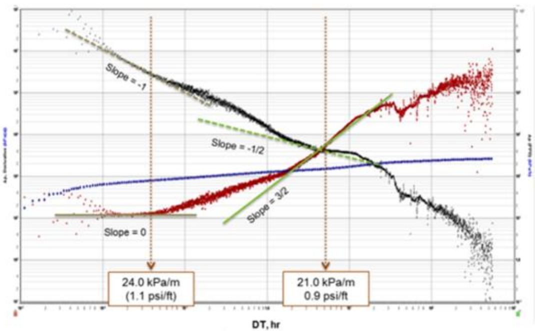




(Abass et al., 1992)

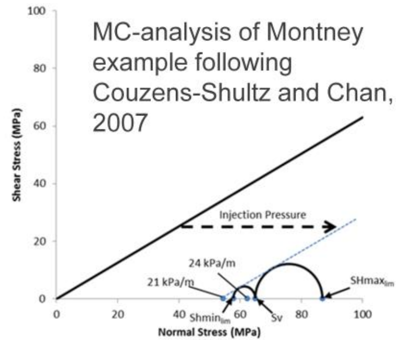


Presenter's notes: In HZ high stress settings, $Sh_{min}$ azimuth well is preferred for transverse fractures, limits fracture turning (tortuousity), thus reducing treating pressure, and favoring proppant placement. In strike-slip settings, hoop stress makes horizontal initiation easier.

# Strength Anisotropy: Implications for Fracturing




SPE 163825




- Increasing awareness of complex fracture behaviour during diagnostic tests
- Complex fracture models, PTA techniques being used to unravel some aspects
- Mechanically, laminations can be shown to be prone to shear failure in NWB region or some distance from tensile initiation

# Summary

- Laminations are important
- Clays, mineralised lenses, organic matter may comprise laminae
- Anisotropy severity and type will depend on this
- Lithology-based mechanical property relationships required
- Strength anisotropy can be constrained and shouldn't be overlooked
- Non-linear models better represent weak planes
  - Eg. Barton-Bandis
  - Roughness and strength of sheared surface control aperture, perm and shear

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