# Seismic fracture detection in the SWS:
## Anisotropic perspectives on an isotropic workflow

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# Outline

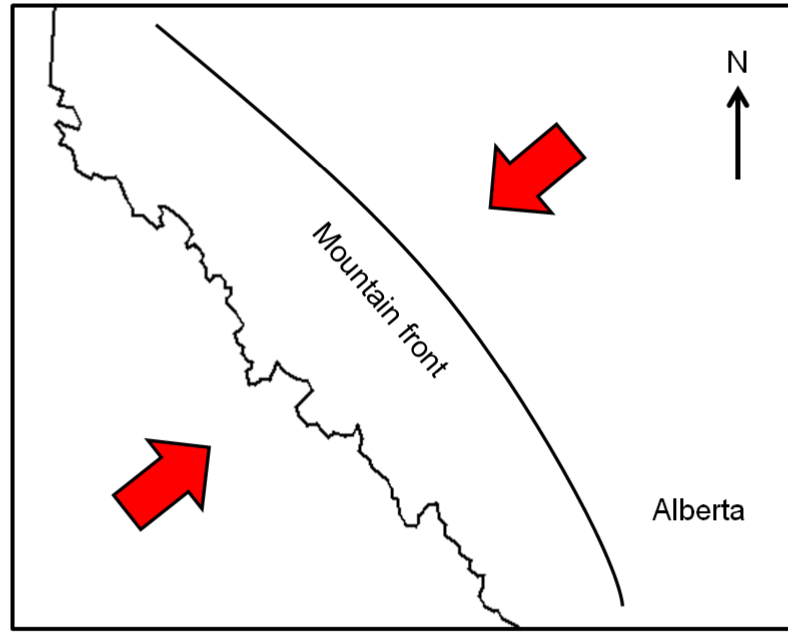
- Introduction
- Fracture detection
  - Seismic discontinuities
  - Elastic properties and failure criterion
  - Residual moveout analysis
- Results
- Conclusions

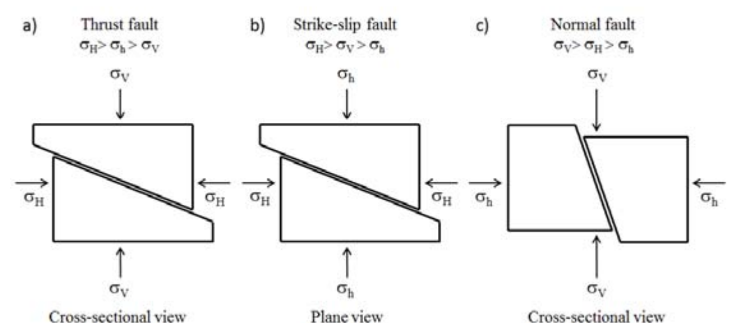
# Geological information

- **Second White Specks**
  - **Upper Cretaceous marine mudstone**
  - **Regionally continuous hydrocarbon system**
  - **> 450 billion barrels OOIP (GSC)**
  - **Production attributed to preferential fracturing**

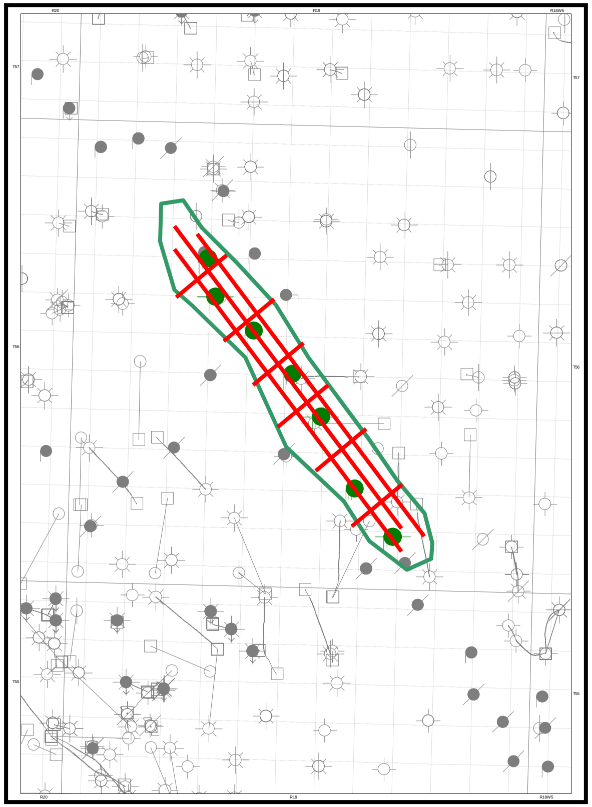
# Stress history

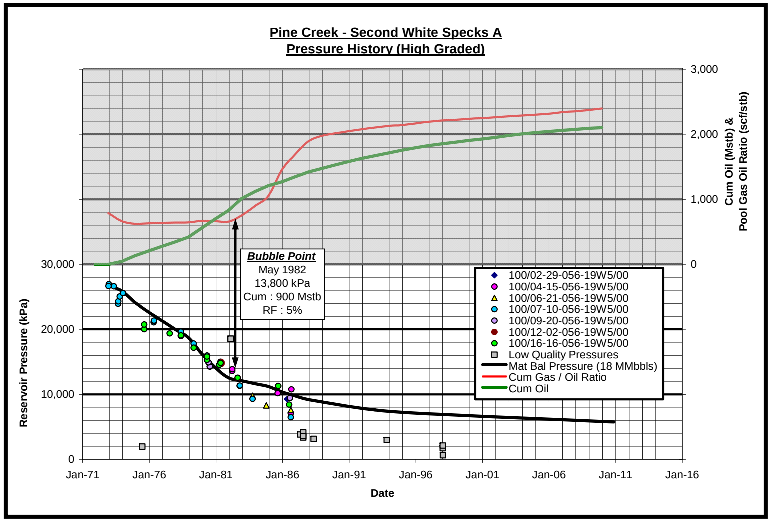
- **Rocky Mountain Building**
  **(Laramide Orogeny, 40-70 Ma)**
  - **Compression**
    - **Thrust faulting stress regime**
    - **Accompanied by structural changes**
  - **Relaxation and additional deposition**
    - **Strike-slip to normal faulting stress regime**



# Pine Creek





Pine Creek - Second White Specks A
Pressure History (High Graded)
Reservoir Pressure (kPa)
Cum Oil (Mstb) &
Pool Gas Oil Ratio (scf/stb)
30,000
20,000
10,000
0
3,000
2,000
1,000
0
Bubble Point
May 1982
13,800 kPa
Cum : 900 Mstb
RF : 5%
100/02-29-056-19W5/00
100/04-15-056-19W5/00
100/06-21-056-19W5/00
100/07-10-056-19W5/00
100/09-20-056-19W5/00
100/12-02-056-19W5/00
100/16-16-056-19W5/00
Low Quality Pressures
Mat Bal Pressure (18 MMbbls)
Cum Gas / Oil Ratio
Cum Oil
Jan-71
Jan-76
Jan-81
Jan-86
Jan-91
Jan-96
Jan-01
Jan-06
Jan-11
Jan-16
Date

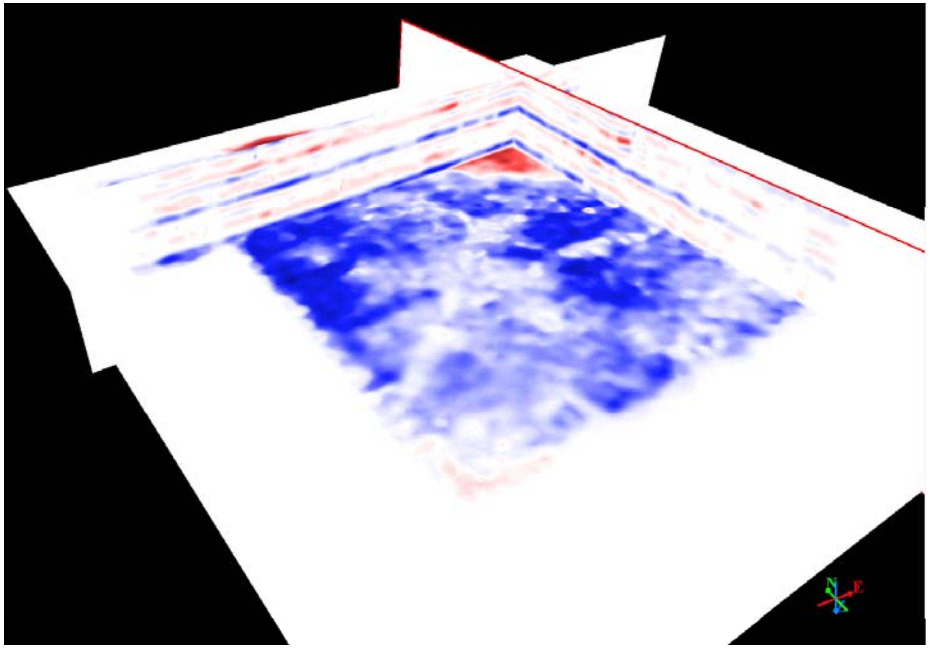

# Thrust fracture detection

## Ant Tracking

Reflection amplitudes

Edge detection

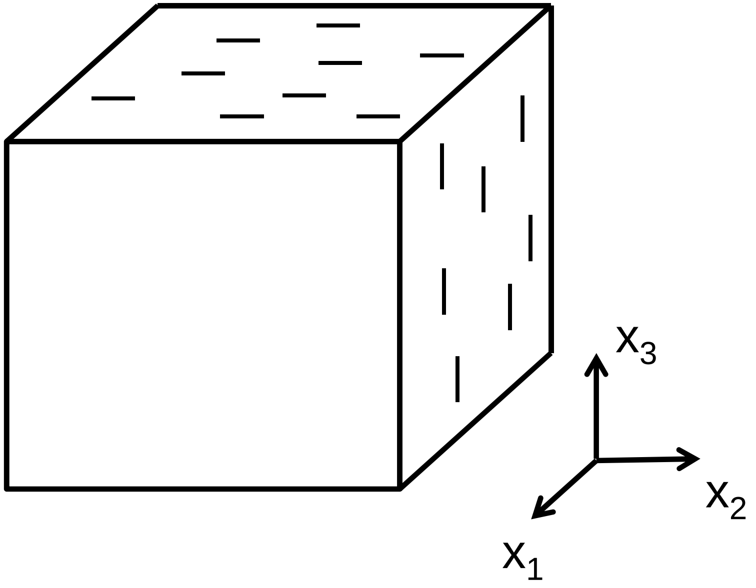
Ant Tracking



# Hudson's crack model

- **Aligned penny shaped inclusions**

$$C_{ij}^{(eff)} = C_{ij}^{(0)} + C_{ij}^{(1)} + C_{ij}^{(2)}$$

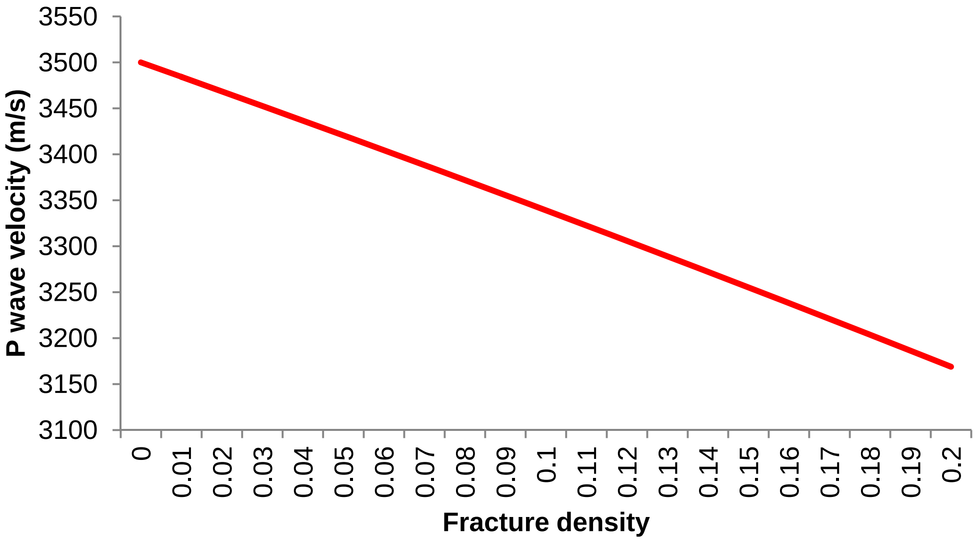



Hudson, J.A., 1981

# Velocity vs. fracture density

- **Increase in fracture density = Decrease in vertical P-wave velocity**

$$V_p^{(eff)} = \sqrt{\frac{C_{33}^{(eff)}}{\rho}} = \sqrt{\frac{1}{\rho}\left(\lambda + 2\mu - \frac{4\lambda^2(\lambda+2\mu)}{3\mu(\lambda+\mu)}\varepsilon\right)}$$



# Brittleness

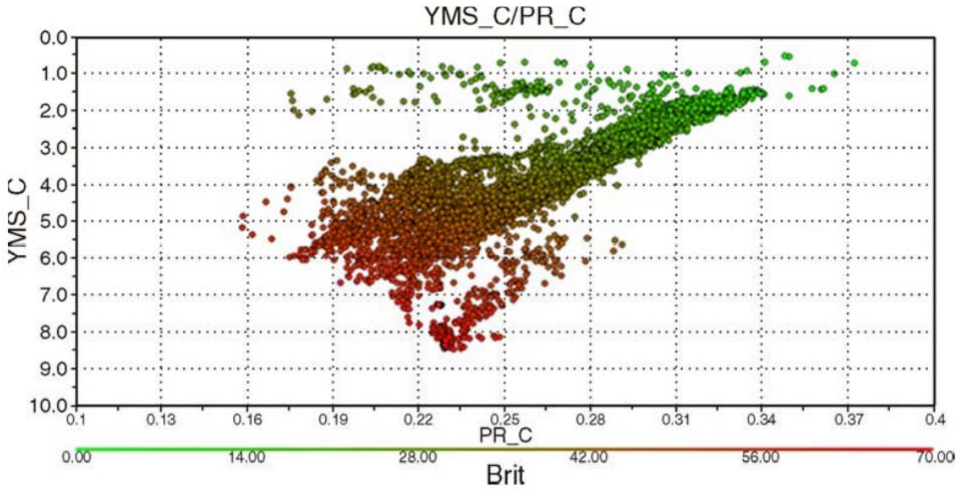
- **Wikipedia definition**
  - **A material is brittle if, when subjected to stress, it breaks without significant deformation (strain).**

# Brittleness

- **Halliburton definition**
  - **Increase brittleness**
    - **Low Poisson's ratio (ν)**
      - **Ability to fail under stress**
    - **High Young's modulus (E)**
      - **Ability to maintain a fracture**

Transverse deformation

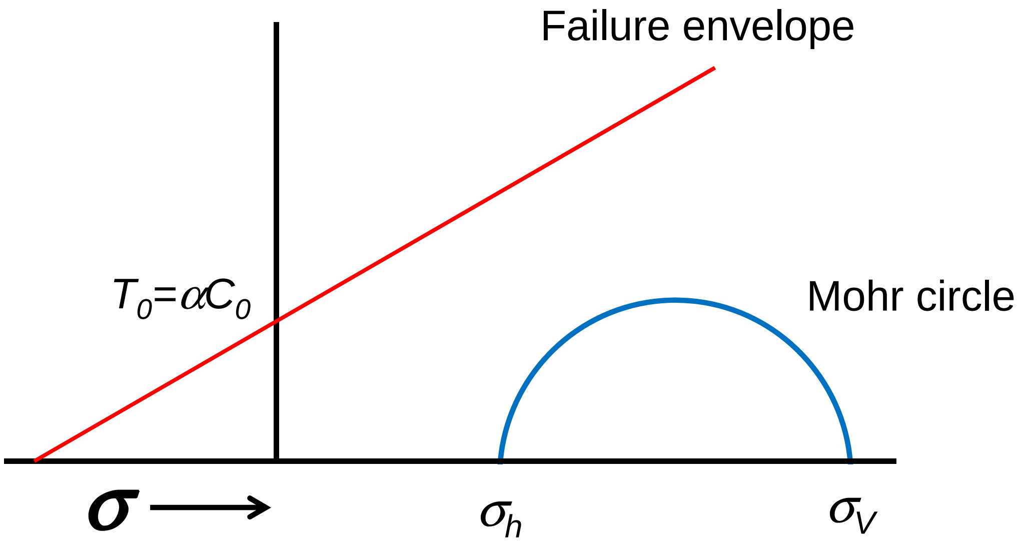
$$\sigma_{closure} = \frac{\nu}{1-\nu}\sigma_V + \frac{E}{1-\nu^2}\left(e_{xx} + \nu e_{yy}\right)$$




Rickman et al., 2008

# Mohr Coulomb failure criterion

- **Failure occurs when Mohr circle touches failure line**
  - **Poisson's ratio**
    - **Size of Mohr circle**
  - **Young's modulus**
    - **Position of failure envelope**

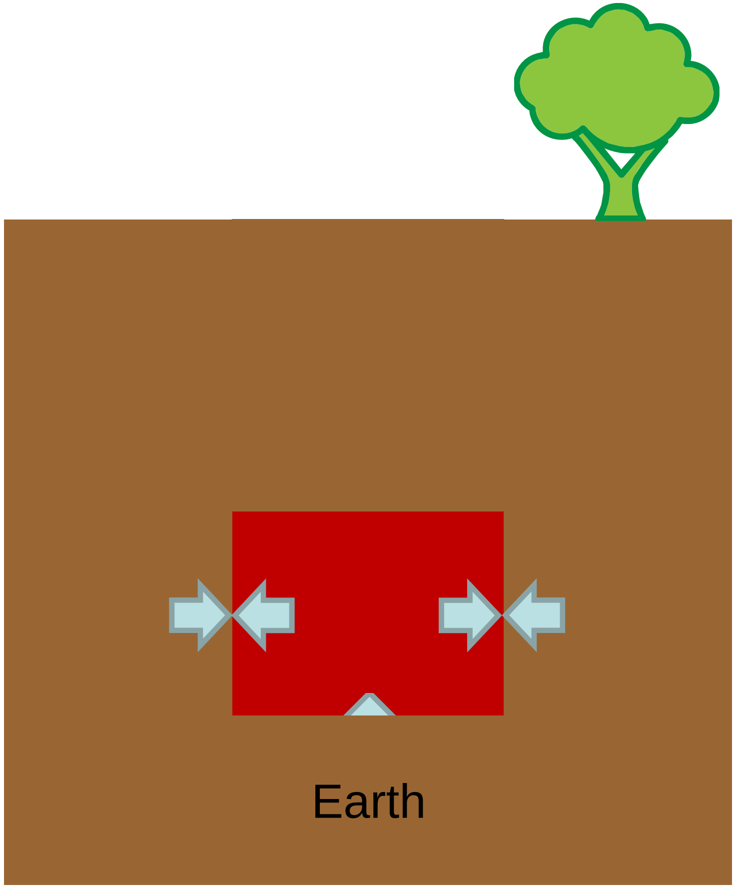


# Uniaxial strain

- **In-situ stress**
  - **Lithostatic**
  - **Tectonic**
  - **Constitutive behavior of the material**

External forces

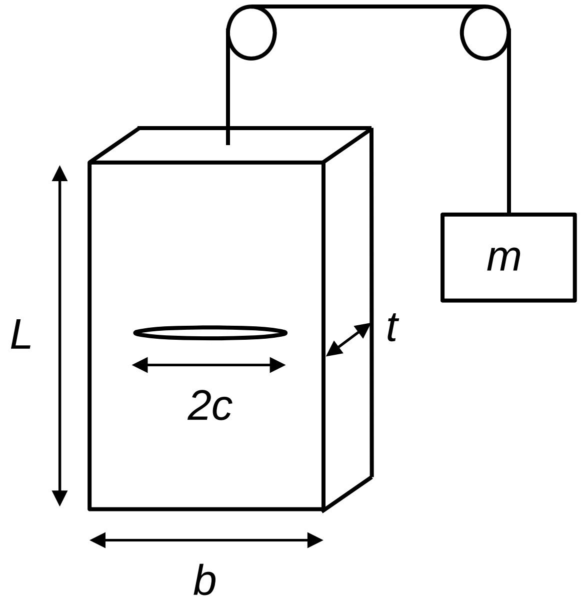
$$\sigma_H = \sigma_h = \frac{\upsilon}{1-\upsilon}\sigma_V$$



# Griffith crack propagation

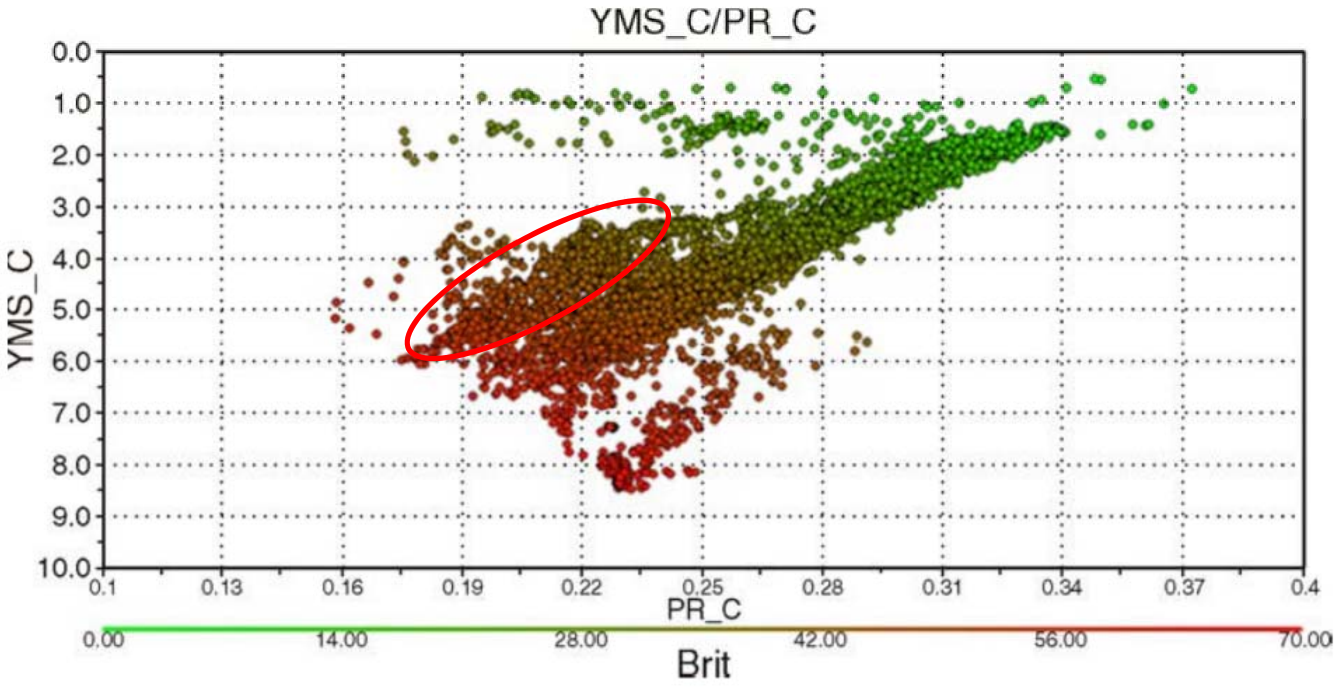
- **Criterion for crack growth derived from thermodynamic principles**

$$T^* = \sqrt{\frac{\pi \gamma E}{4(1-\nu^2)c}}$$



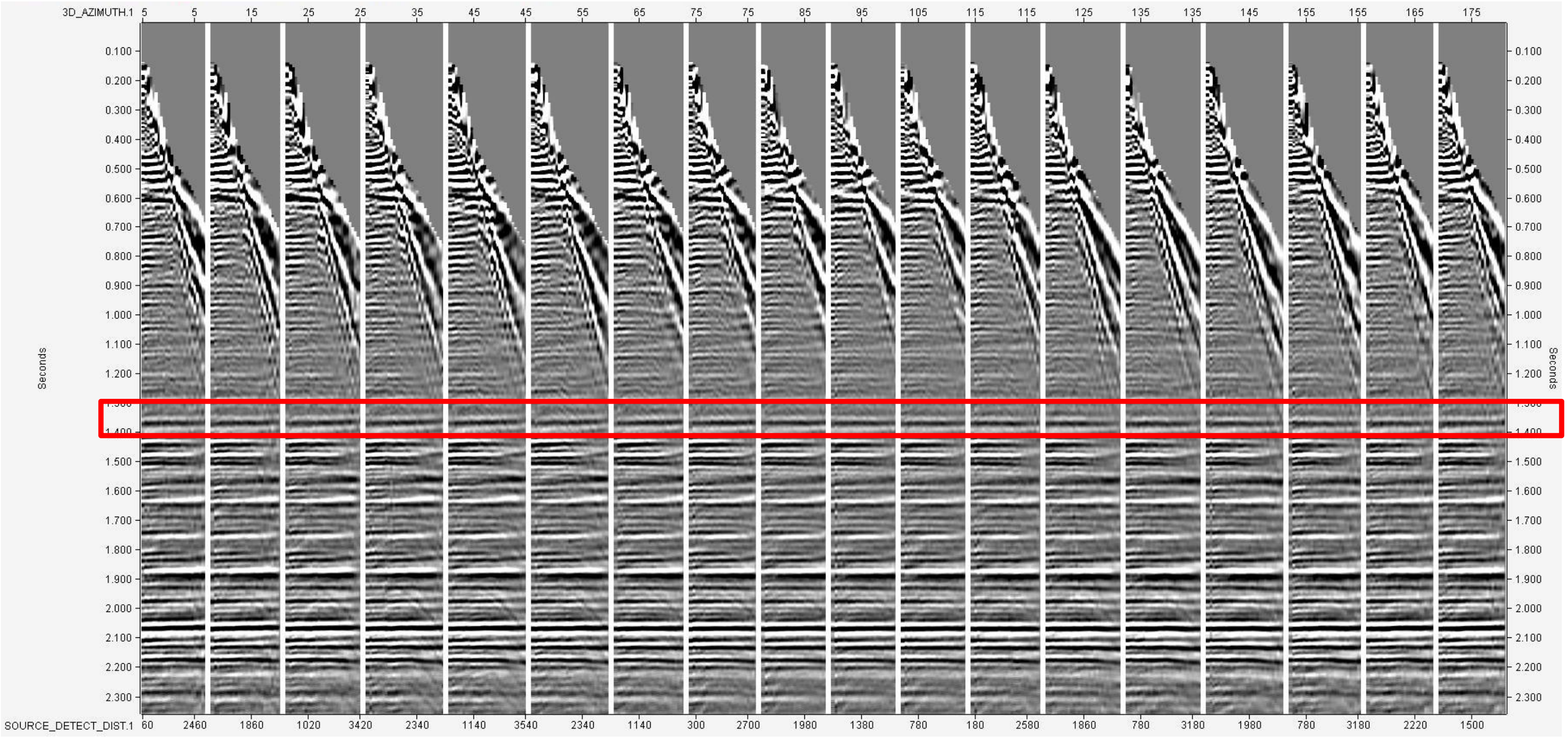
# Constitutive relations

$$E = 3K(1-2\nu)$$



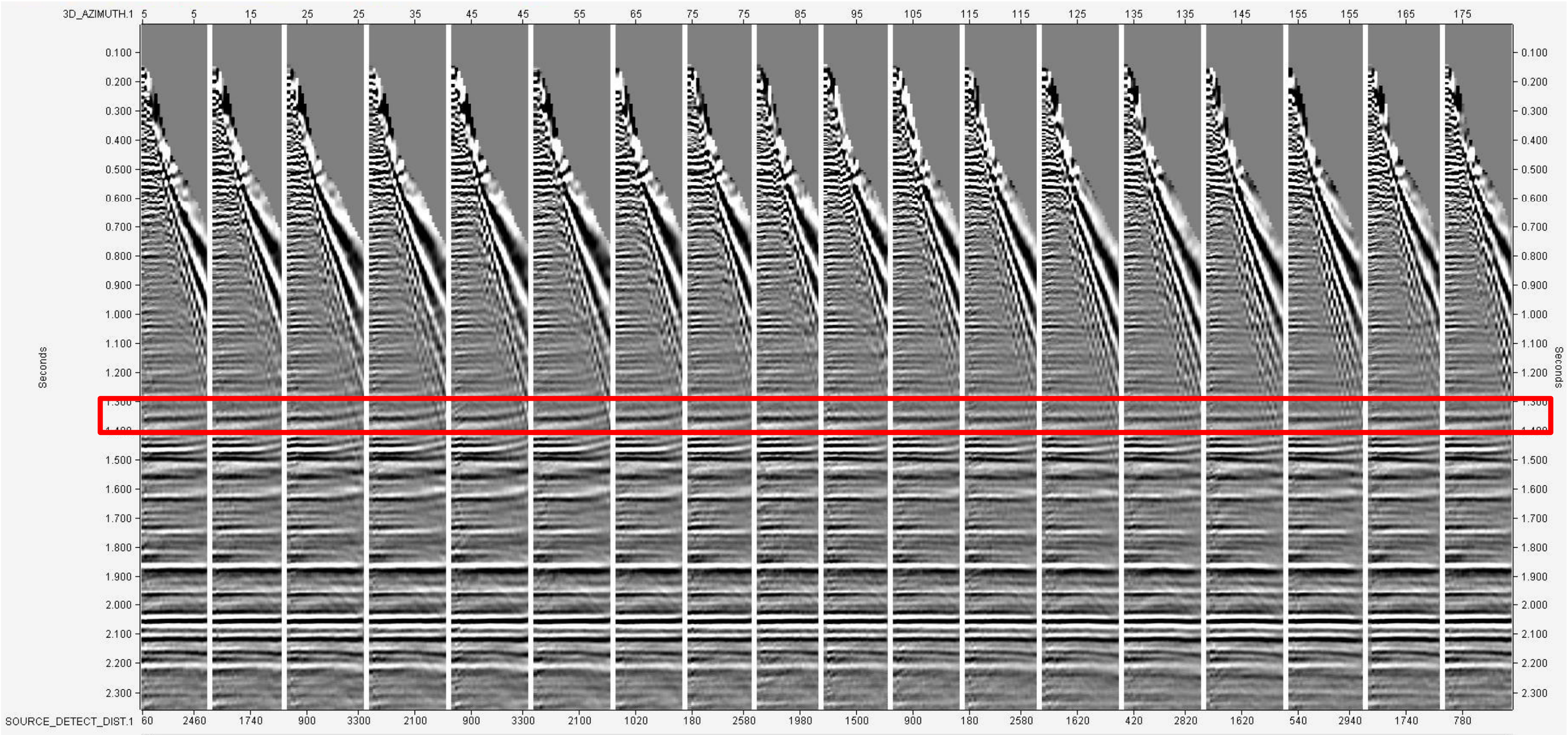
# Azimuthal offset gathers

## No fractures

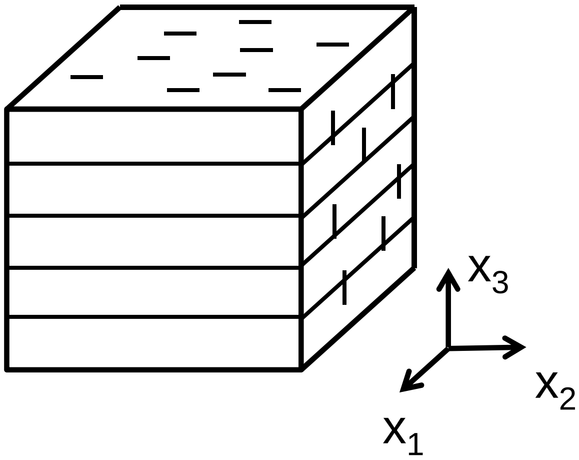


# Azimuthal offset gathers

## With fractures



# Orthorhombic group velocity




**Quasi P-wave group velocity**

$$\frac{1}{V^2(\vec{N})} \approx \frac{N_1^2}{A_{11}} + \frac{N_2^2}{A_{22}} + \frac{N_3^2}{A_{33}} - \frac{E_{12}N_1^2N_2^2}{A_{11}A_{22}} - \frac{E_{13}N_1^2N_3^2}{A_{11}A_{33}} - \frac{E_{23}N_2^2N_2^2}{A_{22}A_{33}}$$

$$E_{12} = 2(A_{12} + 2A_{66}) - (A_{11} + A_{22})$$

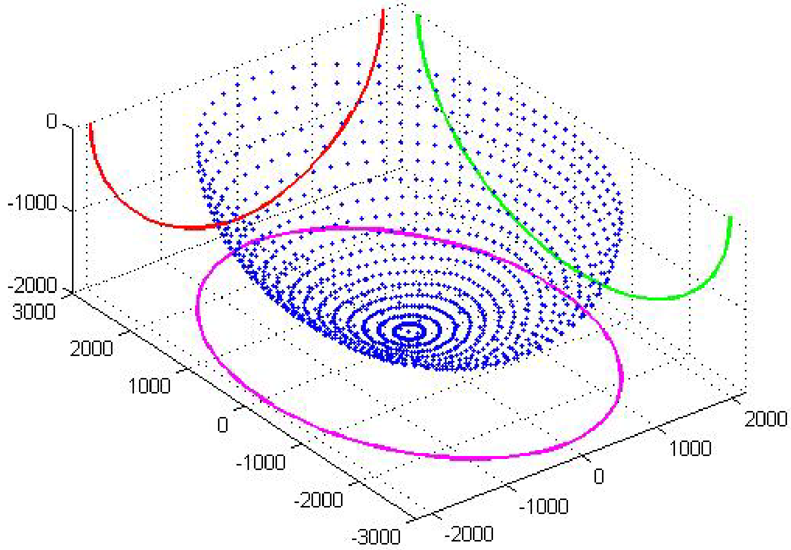
$$E_{13} = 2(A_{13} + 2A_{55}) - (A_{11} + A_{33})$$

$$E_{23} = 2(A_{23} + 2A_{44}) - (A_{22} + A_{33})$$

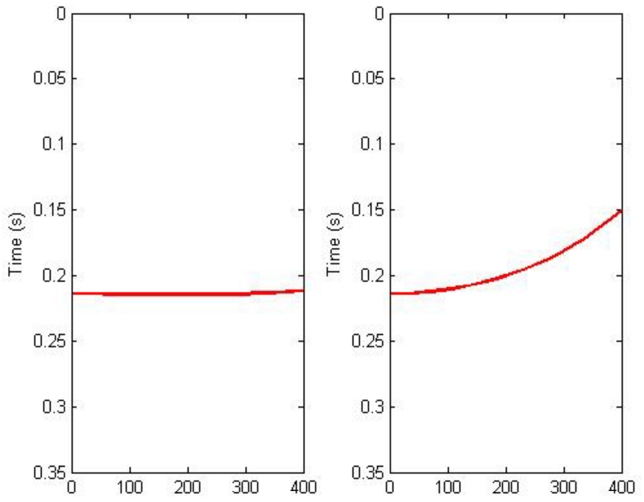
Daley and Krebes, 2006

# Travel time anisotropy effects

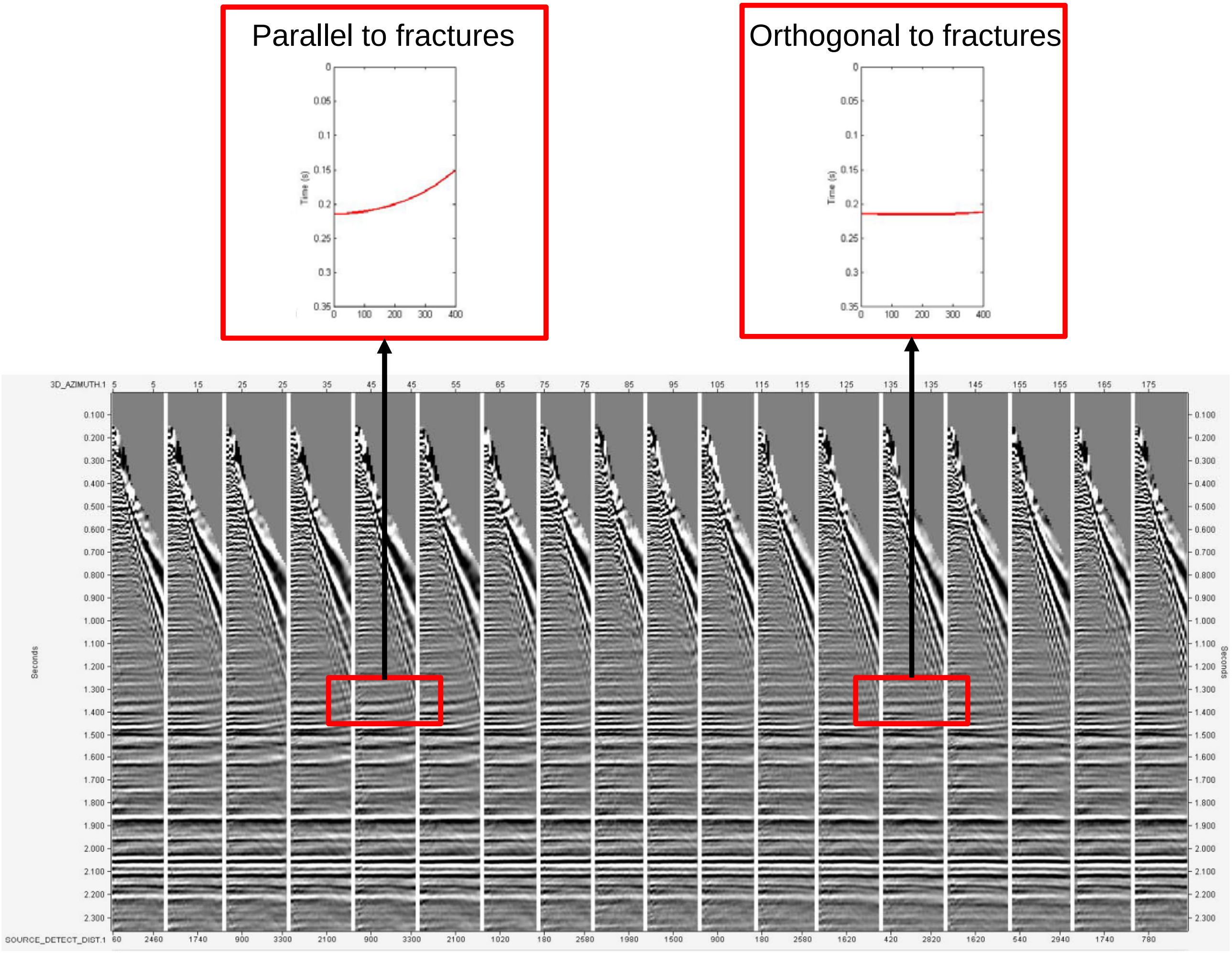
## Anisotropic wavefront

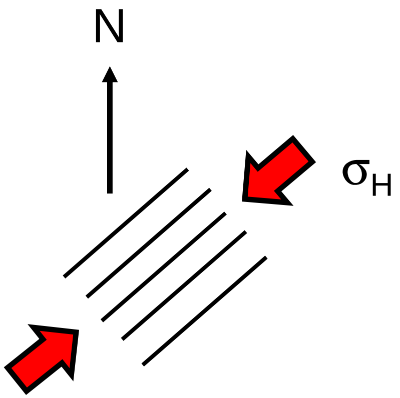



## Isotropic NMO corrected travel time curves



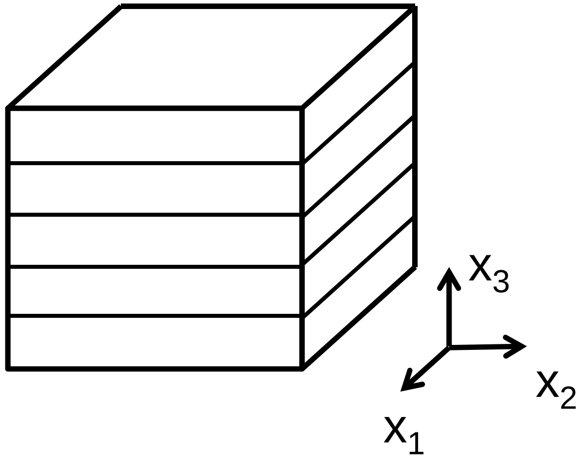
# Travel time anisotropy effects



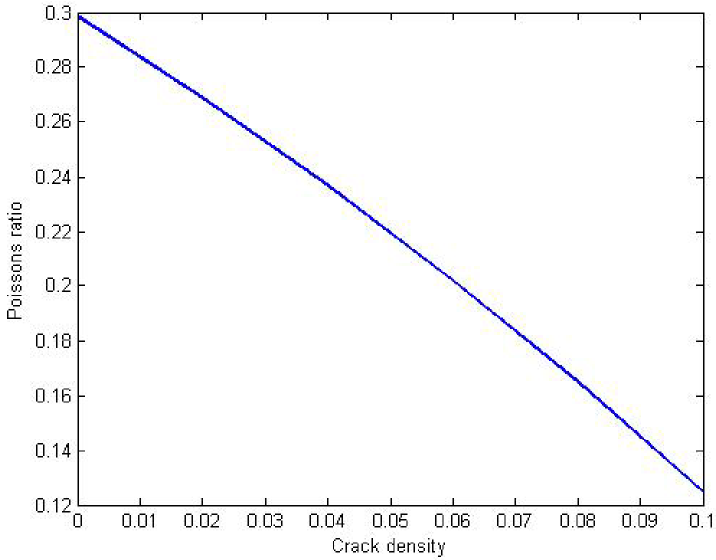

Increased VTI anisotropy = Increased fracturing

# Fracturing in VTI media




$$\nu_{31} = \nu_{32} = \frac{A_{12}A_{23} - A_{22}A_{13}}{A_{11}A_{22} - A_{12}^2}$$

Poisson's ratio



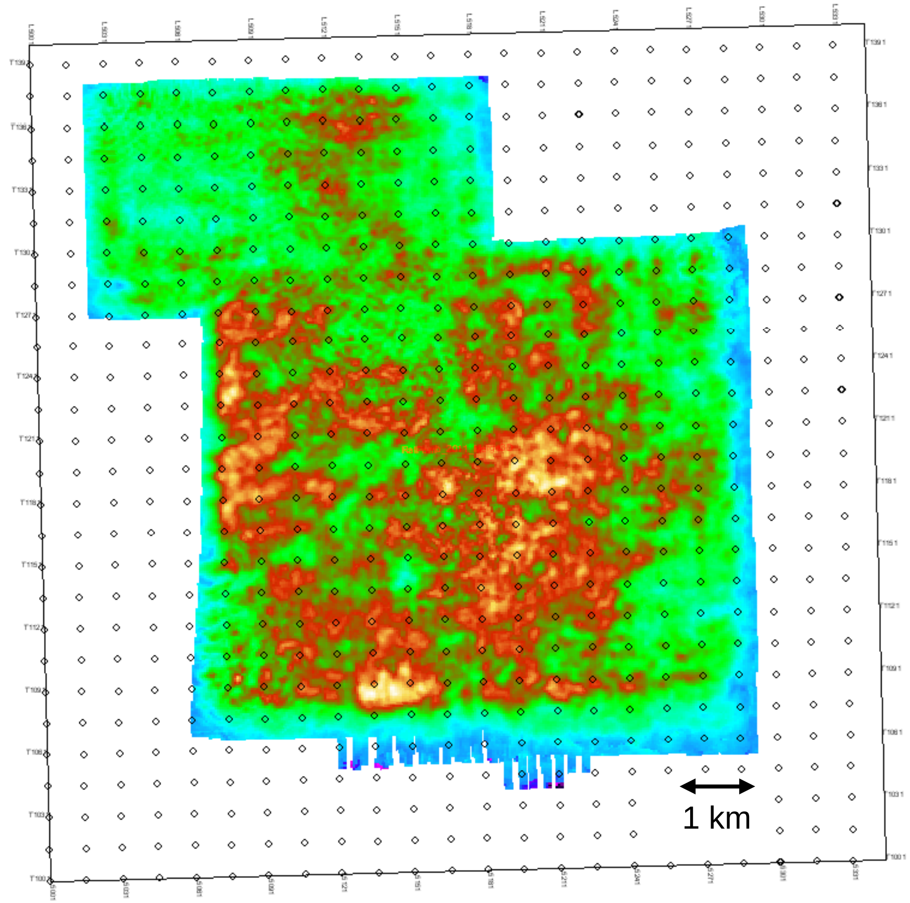
# Attribute maps

Compressional velocity

Poisson's ratio

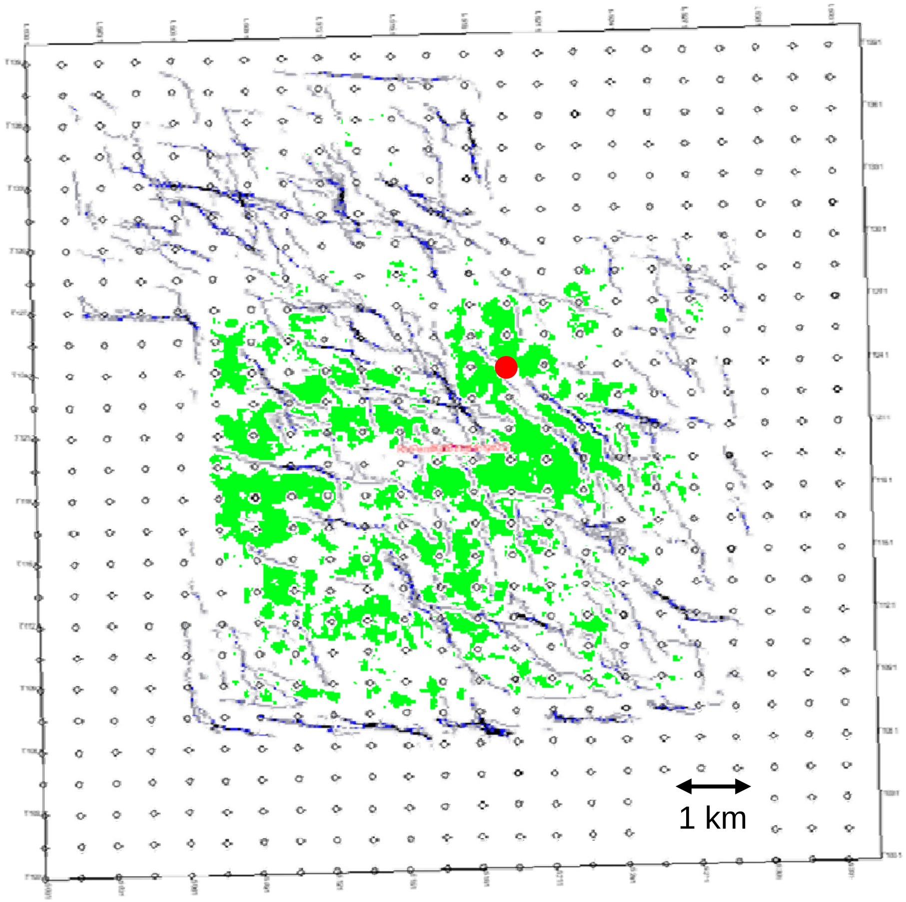
Young's modulus

Travel time anisotropy



# Results

- **Multi-attribute map**
  - **Ant Track features**
    - **Areas of increased probability for thrust fractures**
  - **Green areas**
    - **Combines Vp, PR, YM and anisotropy for defined thresholds**
    - **Areas of increased probability for strike-slip and normal fractures**



# Conclusions

- **Thrust fractures identified through Ant Tracking**
- **Strike-slip and normal fractures identified through multi-attribute analysis**
  - **Compressional wave velocity**
  - **Poisson's ratio**
  - **Young's modulus**
  - **Travel time anisotropy**
- **Seismically derived fracture indicators look promising in reducing exploration risk in the SWS**

Acknowledgements

- Vermilion Energy
- ARCIS
- Jiwu Lin and Greg Cameron (WesternGeco)
- CREWES project