Understanding hydraulic fracture variability through a penny shaped crack model for pre-rupture faults

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ABSTRACT

A study was conducted to investigate the large variations in the hydraulic fracture behavior in the vicinity of faults. The process of failure was illustrated through laboratory experiments that demonstrate the formation of aligned microcracks throughout the deformation process. Using a penny shaped crack model, associated properties can be computed to investigate the response of media containing a fault that has yet to rupture. The reflectivity response for the detection of pre-rupture faults was discussed in addition to the presentation of an effective stress model for a medium containing aligned penny shaped cracks. Using the effective stress model, the observed variations can be understood from the response of the aligned cracks to a uniform normal traction applied by a pore fluid.

INTRODUCTION

- Hydraulic fracture stimulation plays a vital role in the extraction of unconventional energy resources
  - Create permeable pathways for fluid flow to extract or capture energy from subsurface formations
- In the vicinity of faults, variations in the stress field are significant due to mechanical alterations in the rock mass
  - Unexpected fracture behaviors could result
- Continuation of the work performed by Norton et al. (2010) and Maxwell et al. (2011) in the characterization of a tight gas reservoir
  - Understand the mechanisms that control fracture behavior during stimulation
- Present a micromechanical model that seeks to explain the observed fracture behavior

BACKGROUND

- Norton et al. (2010) and Maxwell et al. (2011) combined microseismic measurements and reflection seismic attributes to investigate the variability in hydraulic fracture response in the Montney shale of NE British Columbia, Canada
  - Events SW of Well A are associated with a strike-slip faulting stress regime (conventional hydraulic fracturing)
    - Expected behavior
  - Events along Wells B and C are associated with a thrust faulting stress regime (fault activation)
    - From seismic moment density, *b*-values and composite failure mechanism analysis

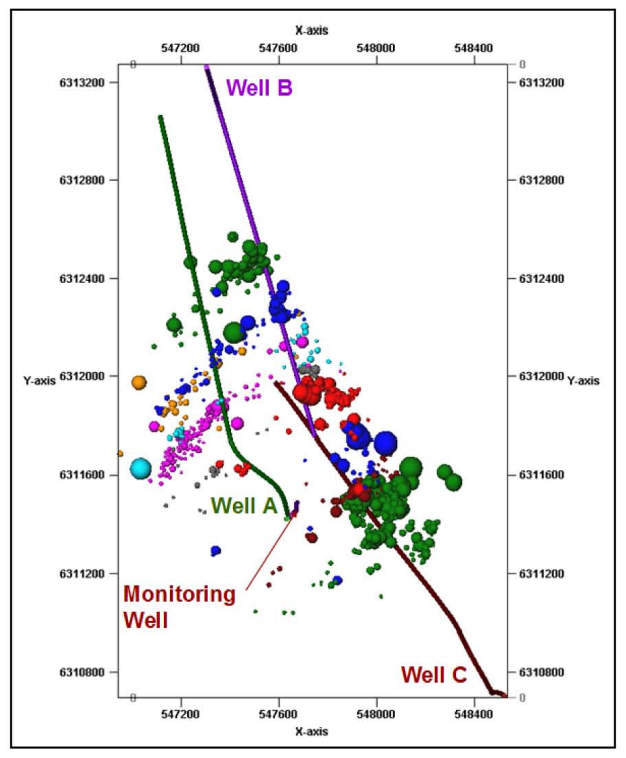


FIG. 1. Map view illustrating the variability in the microseismic response (Maxwell et al., 2011).

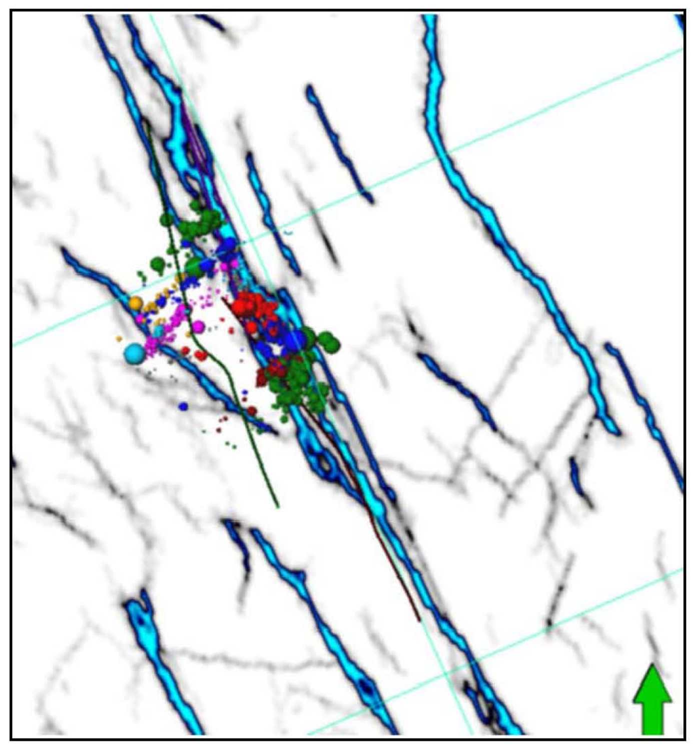


FIG. 2. Microseismic events overlaid on a fault attribute map extracted below the reservoir level.

FAILURE PROCESS

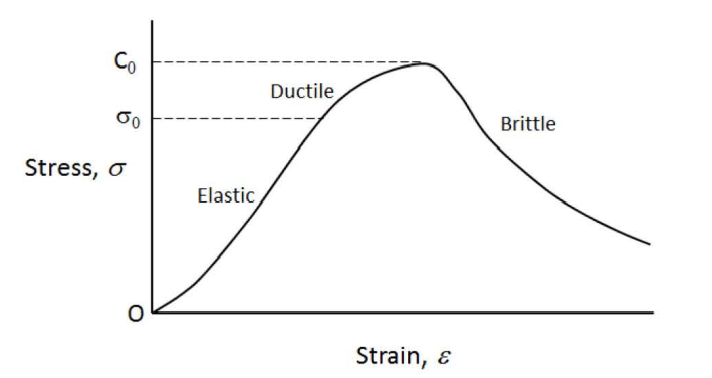


FIG. 3. Stress-strain curve for a rock subject to uniaxial compression.

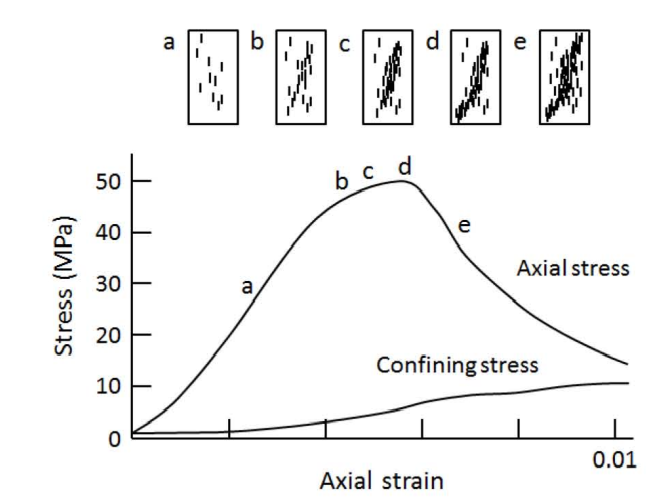
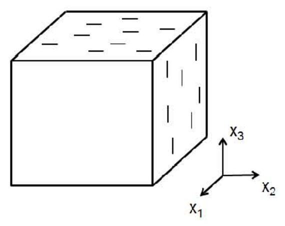


FIG. 4. Hallbauer et al. (1973) experiment. Structural changes at various points along the stress-strain curve (After Jaeger et al., 2007).

REFLECTIVITY RESPONSE

- Hudson's penny shaped crack model



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

- Reflectivity

$$R = \frac{V_2^{(eff)}\rho_2 - V_1^{(eff)}\rho_1}{V_2^{(eff)}\rho_2 + V_1^{(eff)}\rho_1}$$

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

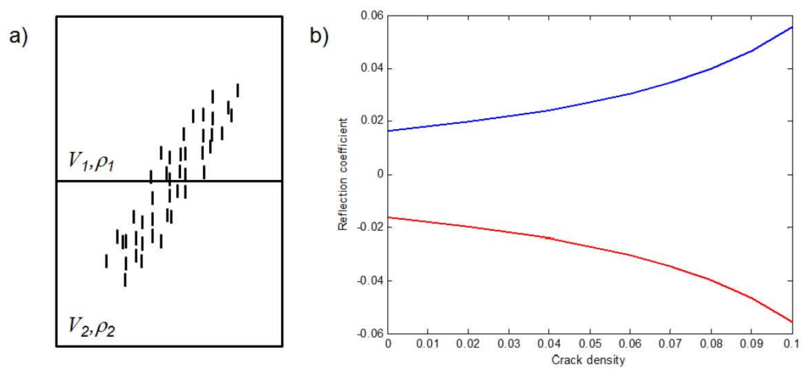


FIG. 6. a) An interface containing aligned microcracks and b) the corresponding reflection coefficients for an increase in impedance (blue) and a decrease in impedance (red) across the interface.

AN EFFECTIVE STRESS MODEL FOR PENNY SHAPED CRACKS

- Derivation
  - **Displacement (Sneddon, 1946)**

$$w(r) = \frac{2(1-\nu)pa}{\pi\mu}\sqrt{1-(r/a)^2}$$

  - **Excess strain energy (Jaeger et al., 2007)**

$$W_{crack} = \frac{1}{2}\int_{2A} pw\,dA = \int_0^{2\pi}\int_0^{a} \frac{2(1-\nu)p^2 a}{\pi\mu}\sqrt{1-(r/a)^2}\,r\,dr\,d\theta$$

$$W_{crack} = \frac{4(1-\nu)p^2a^3}{3\mu}$$

  - **Excess strain energy density in terms of crack density for a volume *V* containing *N* number of cracks**

$$W = \frac{4(1-\nu)p^2\varepsilon}{3\mu}$$

  - **Excess strain**

$$e_{ii}^{(excess)} = \frac{\partial W}{\partial p} = \frac{8(1-\nu)p\varepsilon}{3\mu}$$

  - **Excess stress**

$$\sigma_{ii}^{(excess)} = \frac{8E_i(1-\nu)p\varepsilon}{3\mu} \quad E_1 = \frac{D}{C_{22}^{(eff)}C_{33}^{(eff)} - C_{23}^{(eff)2}} \quad E_2 = \frac{D}{C_{11}^{(eff)}C_{33}^{(eff)} - C_{13}^{(eff)2}} \quad E_3 = \frac{D}{C_{11}^{(eff)}C_{22}^{(eff)} - C_{12}^{(eff)2}} \quad D = \det\begin{vmatrix} C_{11}^{(eff)} & C_{12}^{(eff)} & C_{13}^{(eff)} \\ C_{12}^{(eff)} & C_{22}^{(eff)} & C_{23}^{(eff)} \\ C_{13}^{(eff)} & C_{23}^{(eff)} & C_{33}^{(eff)} \end{vmatrix}$$

  - **Effective stress for aligned penny shaped cracks**

$$\sigma_{ii}^{(eff)} = \sigma_{ii} - \sigma_{ii}^{(excess)} = \sigma_{ii} - \beta p \qquad \beta = \frac{8E_i(1-\nu)\varepsilon}{3\mu}$$

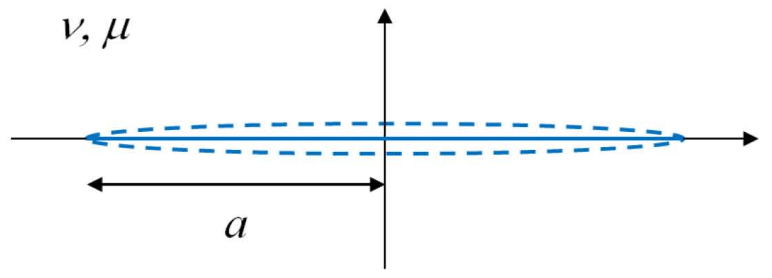


FIG. 7. Schematic for an infinitely thin crack and the associated displacement (dashed line) upon the application of a uniform normal traction.

- β parameter
  - Analogous to the Biot-Willis parameter, α, which represents the proportion of fluid pressure which will produce the same strains as the total stress (Biot and Willis, 1957)
  - Anisotropic due to crack alignment

DISCUSSION

- Region along Wells B and C is hypothesized to be a pre-rupture fault formed in a thrust faulting stress regime
  - Cracks are aligned in the horizontal plane
- Strike-slip faulting stress regime
  - $\sigma_H^{(eff)} > \sigma_V^{(eff)} > \sigma_h^{(eff)}$
- Thrust faulting stress regime
  - $\sigma_H^{(eff)} > \sigma_h^{(eff)} > \sigma_V^{(eff)}$
- Effective vertical stress

$$\sigma_V^{(eff)} = \sigma_V - \alpha p \qquad \sigma_V^{(eff)} = \sigma_V - (\alpha+\beta)p$$

- Effective minimum horizontal stress

$$\sigma_h^{(eff)} = \sigma_h - \alpha p$$

- α calculation (dry pores)

$$\alpha = 1 - K^{(eff)}/K$$

$$1/K^{(eff)} = C^{(eff)} = C + \phi C_p \qquad C_p = \frac{3}{4\mu}$$

- Values for numerical calculations
  - Pressure gradient: 25kP/m, closure stress: 23kP/m, P: 4750m/s, S: 2800m/s, ρ: 2650kg/m^3, ε and ϕ: 0.05
  - α=0.05, β=0.19

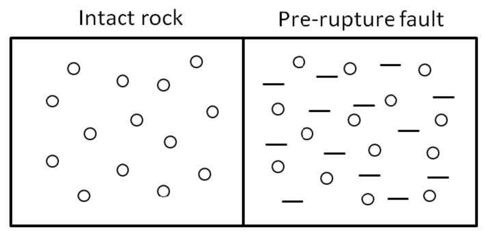


FIG. 8. Model for the intact rock and the pre-rupture fault.

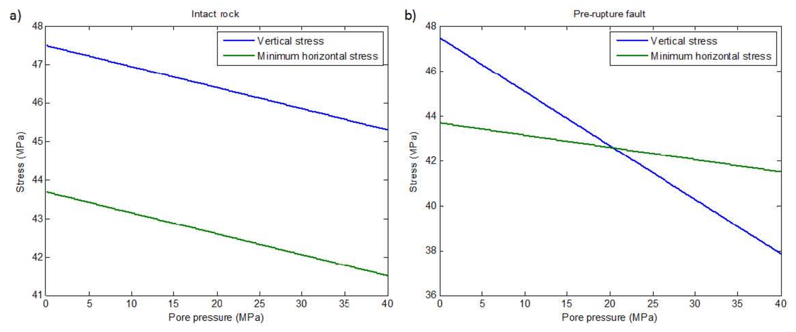


FIG. 9. Effective vertical and minimum horizontal stress for a) the intact rock and b) the pre-rupture fault.

ACKNOWLEDGEMENTS

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