Hydraulic fracturing and its relationship to induced seismicity in time and space

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In the Crooked Lake area, steeply dipping faults are activated by:
- elevated pore-pressure (→ persistent seismicity, timescale ~months)
- poroelastic stress change (→ transient seismicity, mainly confined to treatment interval)

Marcellus: focal mechanisms for composite events
Northern Montney: Empirical Hazard Matrix
Finite Element fault simulations:
- role of cohesion for well healed (inactive) faults
- large surface displacement for shallow reverse faults

Some current activities
Crooked Lake Area: W2015

Days after 2015/01/01

- 117˚30'
- 117˚24'
- 117˚18'
- 117˚12'
- 54˚30'
- 54˚24'

Injection well

\[ \Sigma = -2.7 \]

\[ \Sigma = -1.7 \]

\[ \Sigma = -1.5 \]

\[ \Sigma = -1.5 \]

M<sub>W</sub> < 2

2 ≤ M<sub>W</sub> < 3

M<sub>W</sub> ≥ 3

Crooked Lake Area: W2015

Bao and Eaton, SSA 2016
Largest event during flowback – but unusually low fluid recovery
Episodic seismicity persists throughout W2015 (S1, S2, S3) but not typical aftershock sequence
Maximum magnitude (M_w 3.9) compatible (barely) with McGarr formula

Bao and Eaton, SSA 2016
Remote Triggering of S2?

Bao and Eaton, SSA 2016
Multiple strands – varying response

East: transient
West: persistent

Bao and Eaton, SSA 2016
Marcellus Experiment (2014)

10 portable broadband stations installed to record 11-well treatment

See poster by Zhang and Eaton
Focal mechanism of composite events

Depth Section

Focal Mechanism - jackknife test

Sh/P ratio

See poster by Zhang and Eaton
Montney Seismicity

$M_W = 4.6$

2015/08/18

$h = 4\text{ km}$

Mahani et al., BSSA, in press

BC OGC 2014
Finite-Element Modelling

- 2-D FE simulation yields realistic scaling, including slip/area, stress drop, shape factor and dynamic overshoot.
- Predicts simple model for co-seismic stress drop tensor.
- Unlike active fault systems, cohesion may exert a significant control on fault rheology.

\[ \tau = \mu_0 (\sigma - P_p) + C_0 \]

\[ \tau = \mu_r (\sigma - P_p) \]

Modified from Sattari and Eaton, Tectonophysics, in review.
Amplified ground displacement?

Shallow Reverse Fault

Cohesion 15 MPa, fr.=0.1

See poster by Sattari and Eaton
Earthquakes on Dipping Faults: The Effects of Broken Symmetry

David D. Oglesby, Ralph J. Archuleta,* Stefan B. Nielsen

Dynamic simulations of earthquakes on dipping faults show asymmetric near-source ground motion caused by the asymmetric geometry of such faults. The ground motion from a thrust or reverse fault is larger than that of a normal fault by a factor of 2 or more, given identical initial stress magnitudes. The motion of the hanging wall is larger than that of the footwall in both thrust (reverse) and normal earthquakes. The asymmetry between normal and thrust (reverse) faults results from time-dependent normal stress caused by the interaction of the earthquake-generated stress field with Earth’s free surface. The asymmetry between hanging wall and footwall results from the asymmetric mass and geometry on the two sides of the fault.

www.sciencemag.org • SCIENCE • VOL. 280 • 15 MAY 1998

See poster by Sattari and Eaton
Hazard Matrix Approach

**Red?** - Consider alternate injection site or significantly altering operations.

**Amber?** - Consider alternate injection site or adjusting operational factors.

**Green?** - Continue operations as planned.

*Walters et al., SRL, 2015*
Construct a “hit map” as follows.

1. For each recorded event, assign an operational factor (e.g. cumulative volume) and activity level (e.g. maximum prior event within a specified time window).

2. Test for “hit” – occurrence of a subsequent event that meets criteria (e.g. magnitude, time window).

3. If hit, add zeros, ones to map as shown.
Northern Montney EHMs

Hit Map: $M \geq 1$ in next 4 days

Tipping Point?

Data source: Mahani et al., BSSA, in press

Courtesy M. Rempel, BSc senior thesis project
Northern Montney EHMs

Hit Map: $M \geq 2.5$ in next 21 days

Tradeoff?

Aftershocks

Foreshocks

Data source: Mahani et al., BSSA, in press
Current Activities

- Developing a Python-based workflow for matched-filtering analysis
- Applying this approach to W2016 seismicity, using RV, DS (NMX/UC) and other networks

See poster by Vragov and Eaton
Current Activities

- Ongoing frac program (started this week)
- Dual monitoring: induced seismicity and microseismic
- 6 broadband stations + accelerometer installed for UC by NMX
- Holdback on data release

Image courtesy of Michael Laporte, Nanometrics
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• Ali Mahani (preprint of northern Montney BSSA paper)