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

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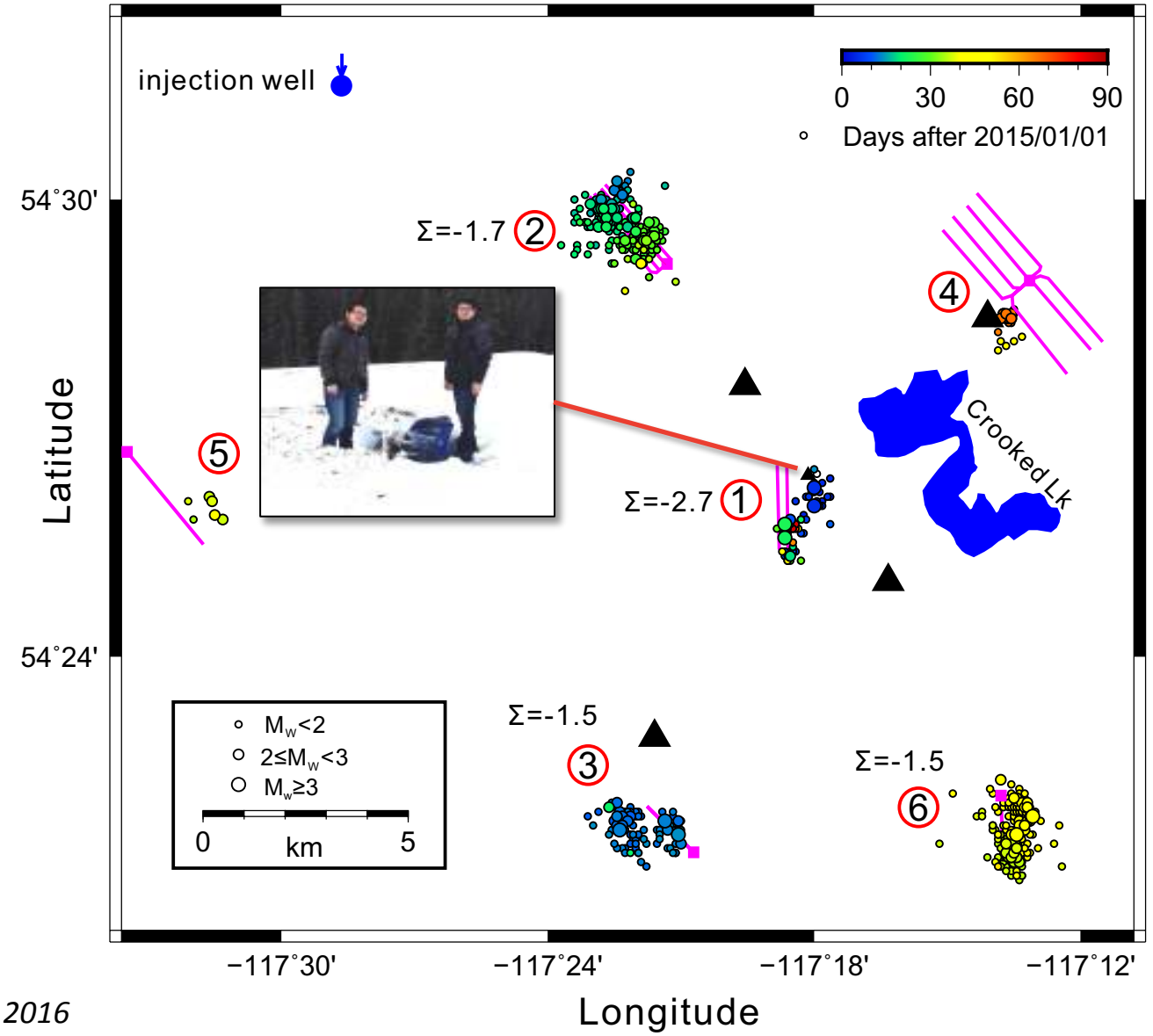
Key Points

- 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

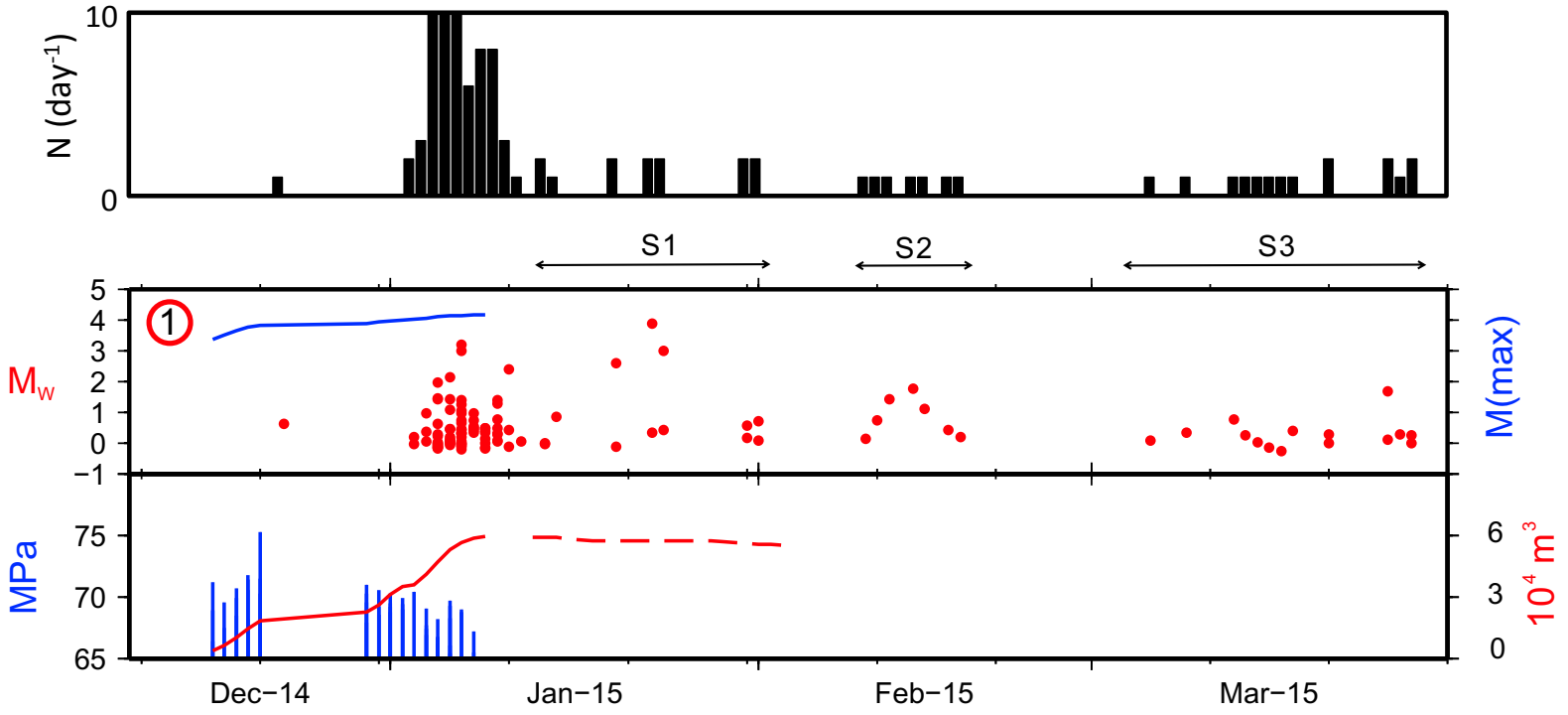
Crooked Lake Area: W2015



Bao and Eaton, SSA 2016

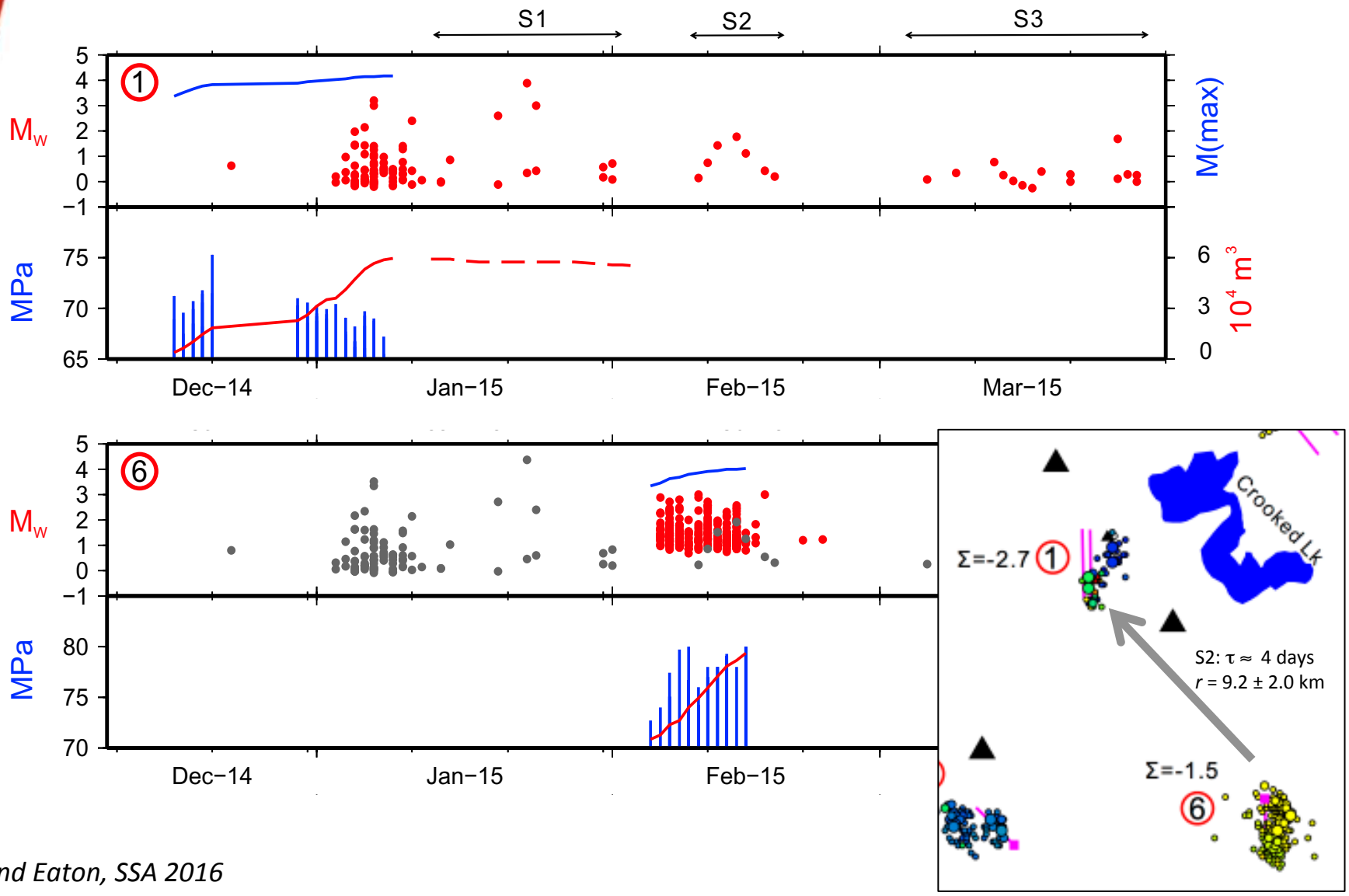
Seismicity vs. Injection Data

- 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

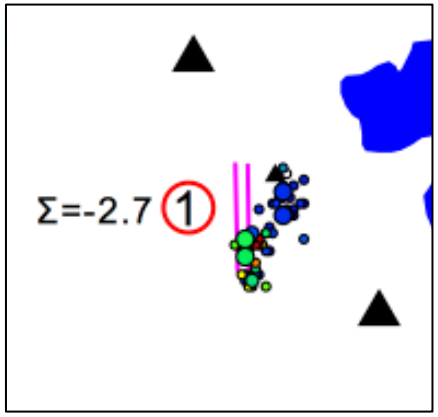
Remote Triggering of S2?

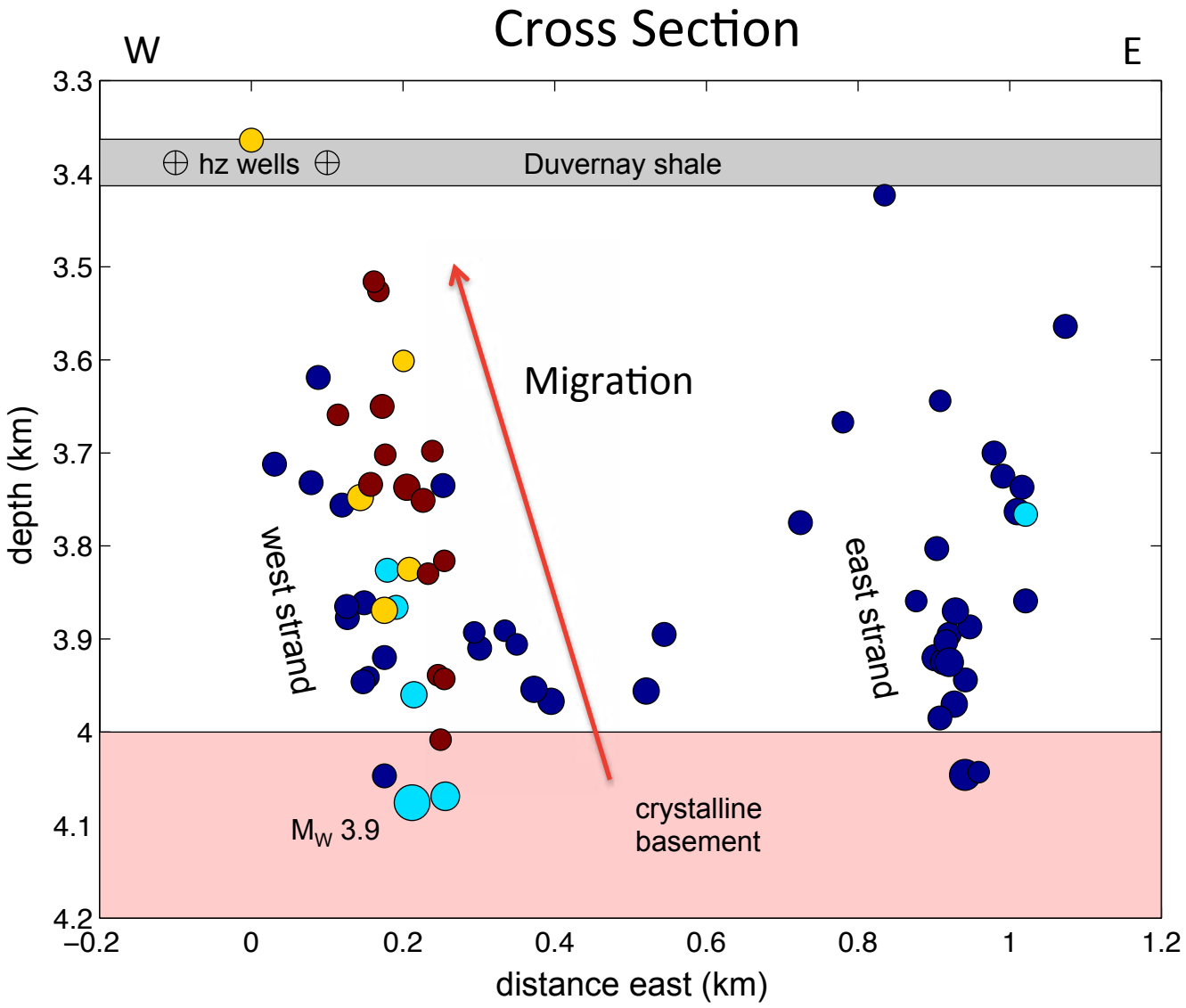


Bao and Eaton, SSA 2016

Multiple strands – varying response

East: transient
West: persistent

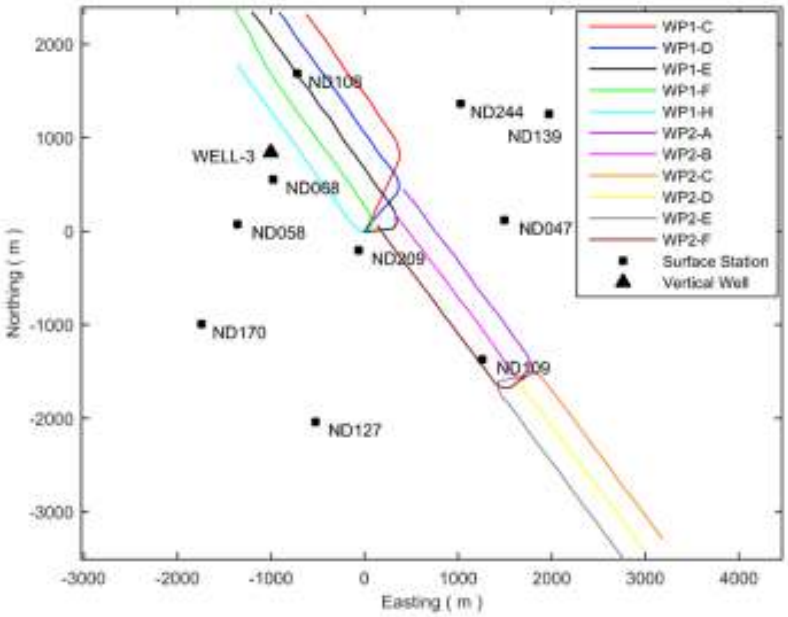




Bao and Eaton, SSA 2016

Marcellus Experiment (2014)

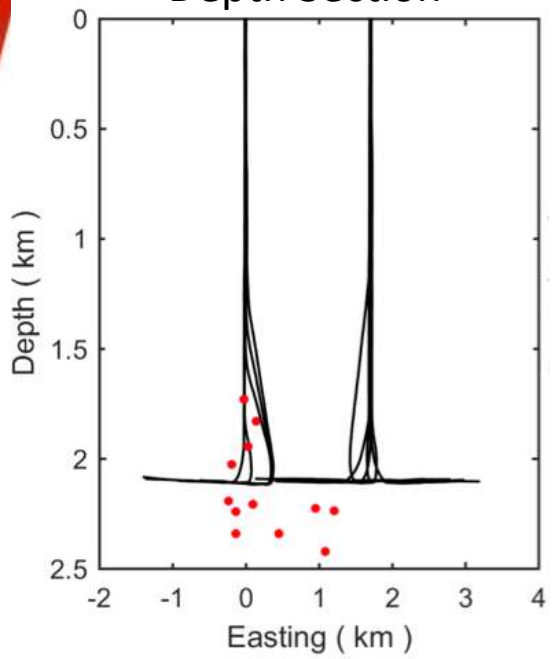
10 portable broadband stations installed to record 11-well treatment



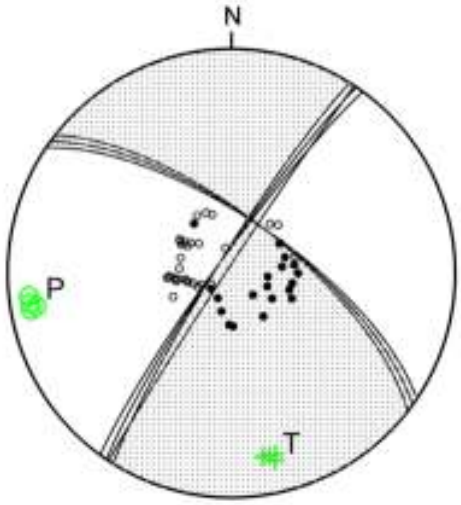
See poster by Zhang and Eaton

Focal mechanism of composite events

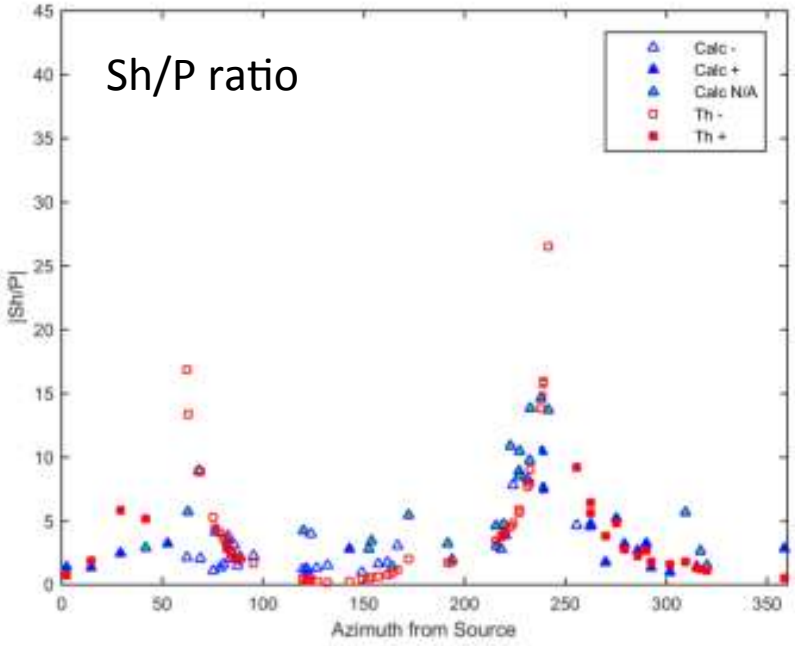
Depth Section



Focal Mechanism
- jackknife test



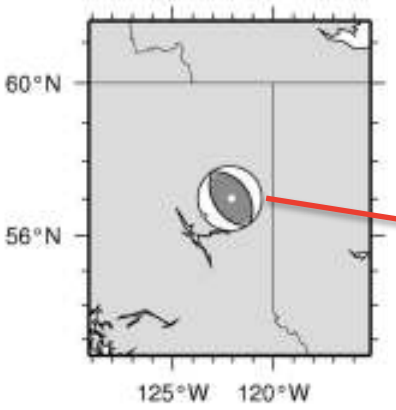
Sh/P ratio

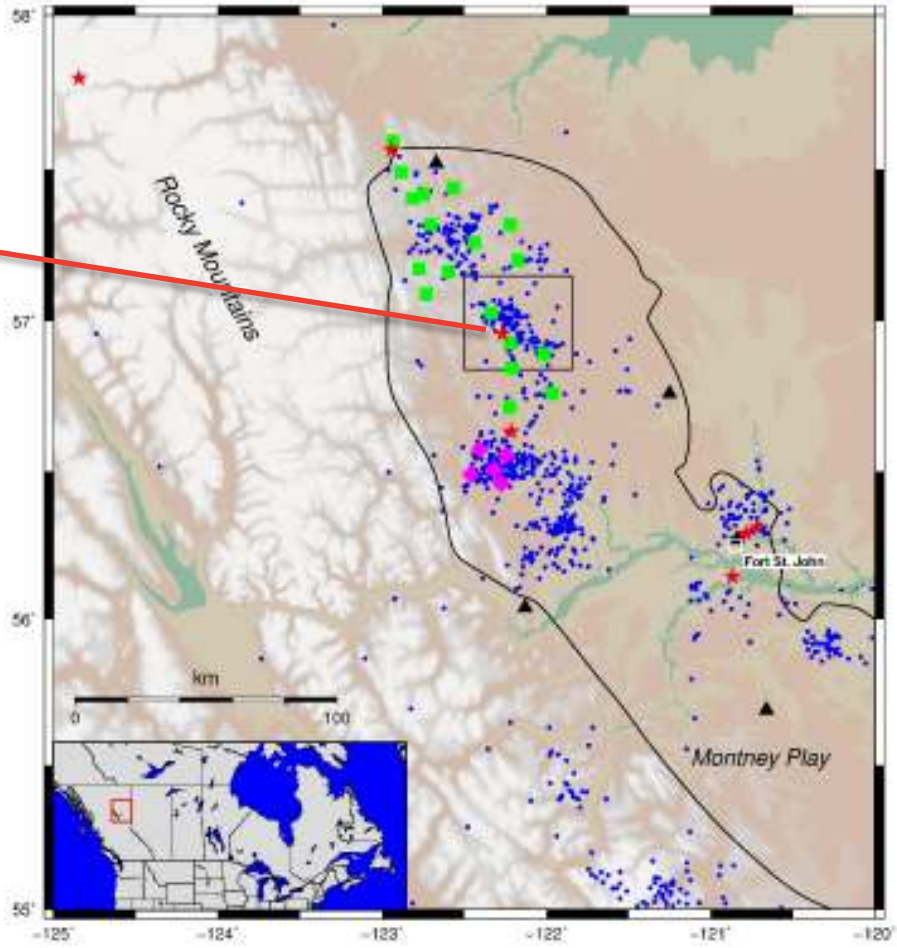


See poster by Zhang and Eaton

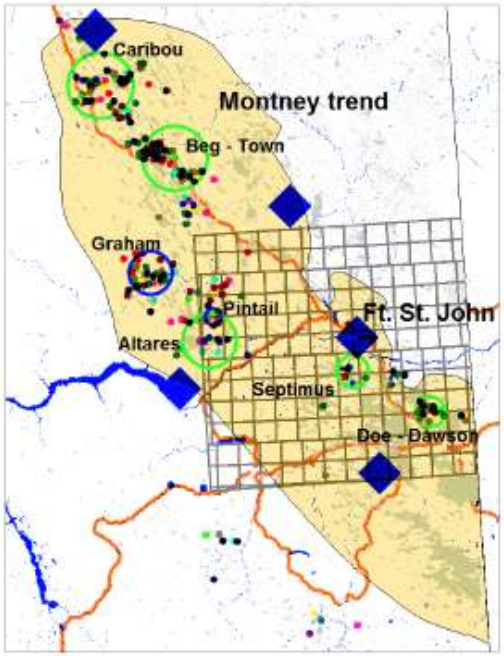
Montney Seismicity

M_W 4.6
2015/08/18
h = 4 km





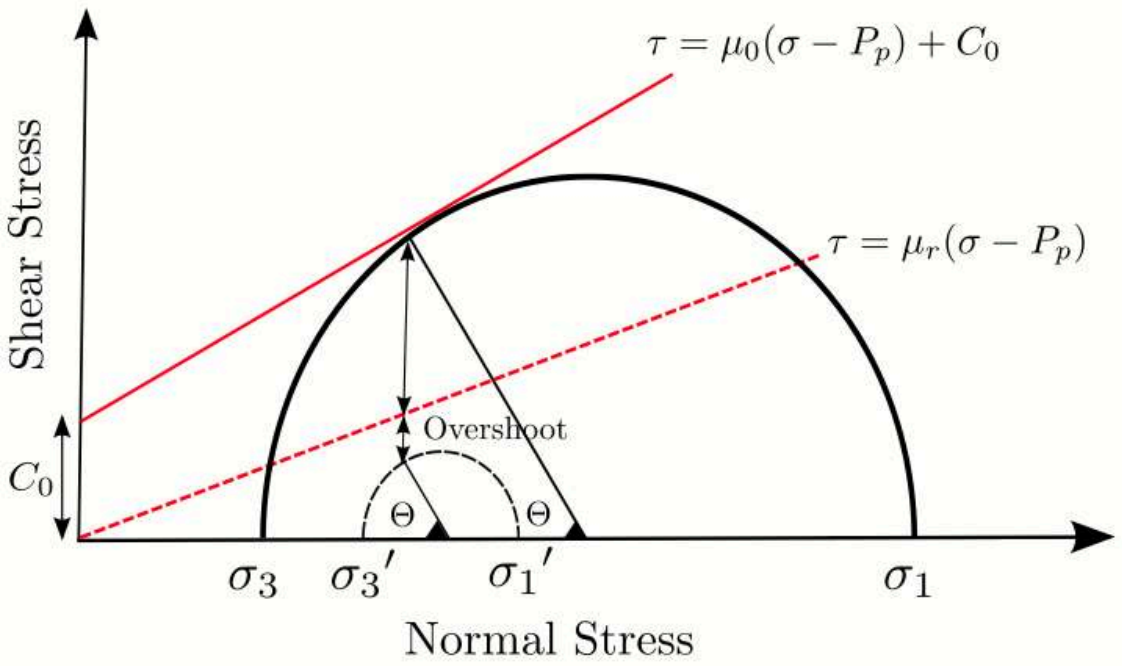
Mahani et al., BSSA, in press



BC OGC 2014

Finite-Element Modelling

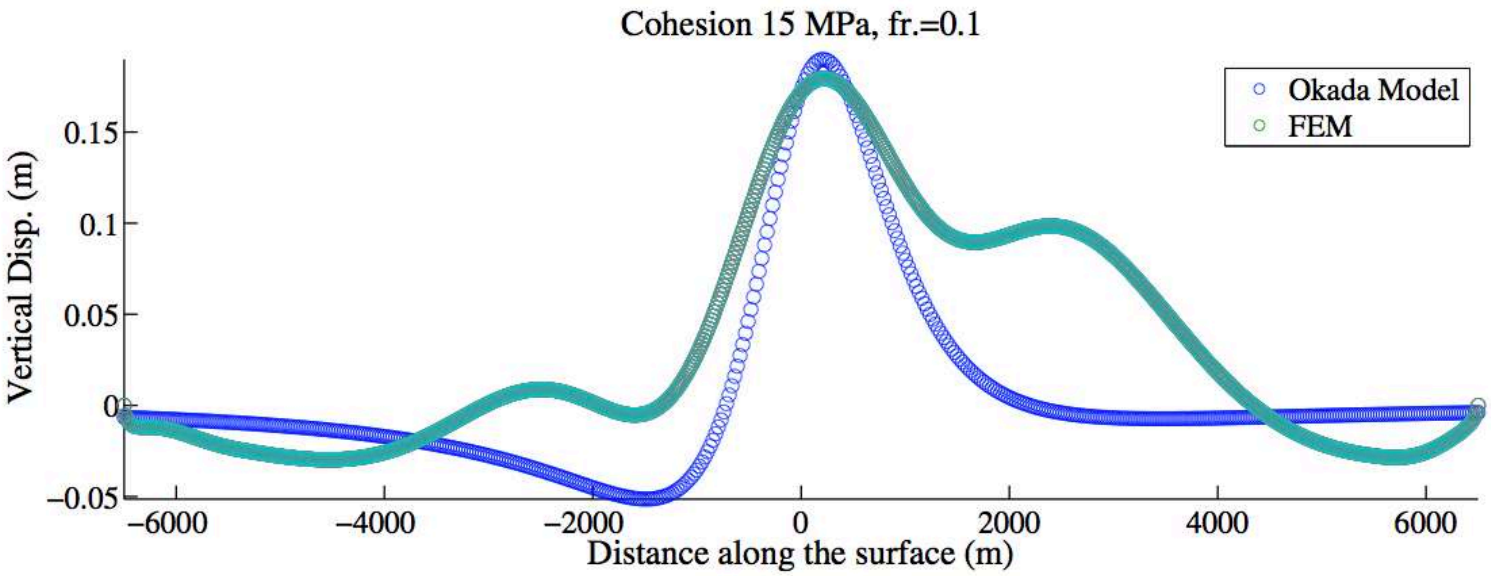
- 2-D FE simulation yields realistic scaling, including slip/area, stress drop, shape factor and dynamic overshoot
- Predicts simple model for co-seismic stress drop tensor
- Unlike active fault systems, cohesion may exert a significant control on fault rheology



Modified from Sattari and Eaton, Tectonophysics, in review

Amplified ground displacement?

Shallow Reverse Fault



See poster by Sattari and Eaton

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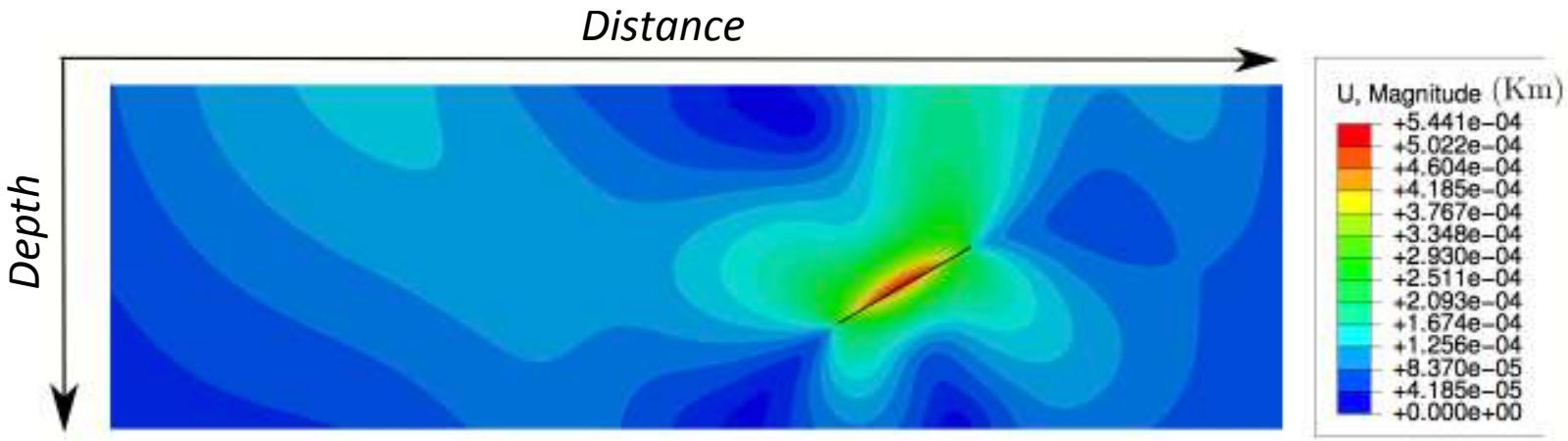
Free-surface effect

Earthquakes on Dipping Faults: The Effects of Broken Symmetry

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

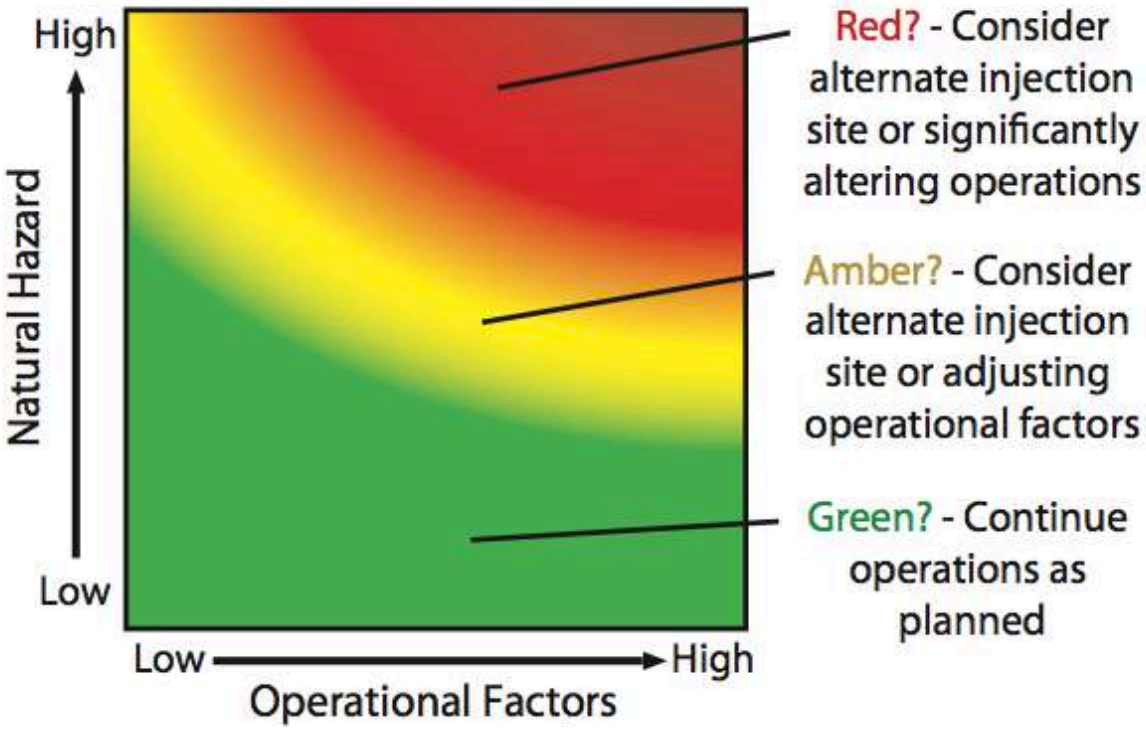
Dynamic simulations of earthquakes on dipping faults show asymmetric near-source ground motion caused by the asymmetric geometry of such faults. The ground motion from a thrust or reverse fault is larger than that of a normal fault by a factor of 2 or more, given identical initial stress magnitudes. 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



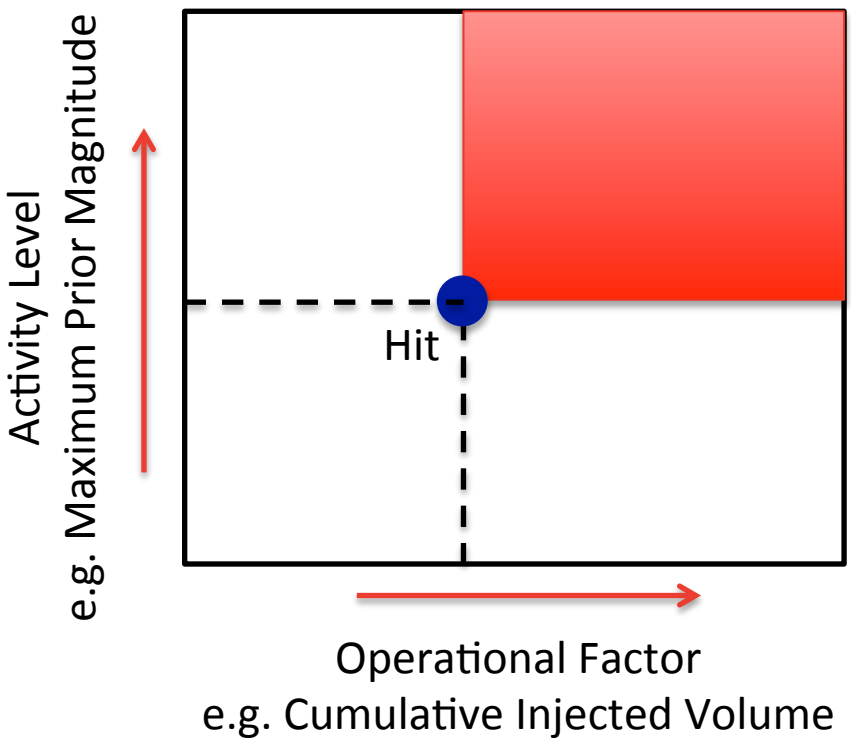
See poster by Sattari and Eaton

Hazard Matrix Approach



Walters et al., SRL, 2015

Empirical Hazard Matrix



Construct a "hit map" as follows.

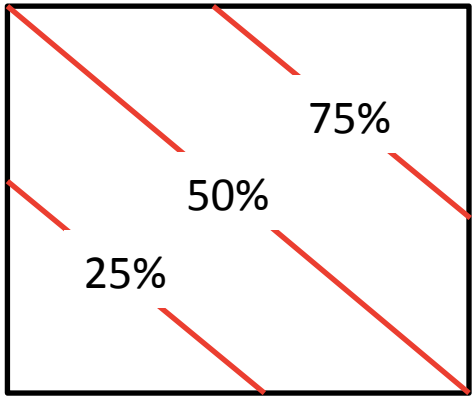
1. For each recorded event, assign an operational factor (e.g. cumulative volume) and activity level (e.g. maximum prior event within a specified time window).

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

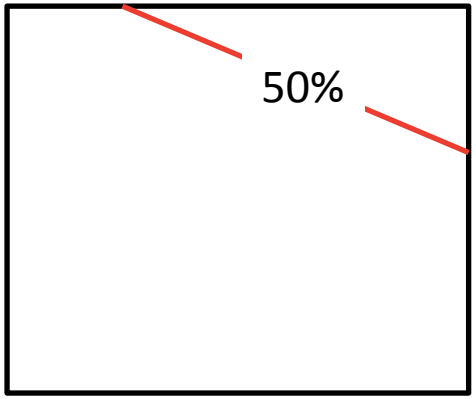
3. If hit, add zeros, ones to map as shown.

EHM Templates

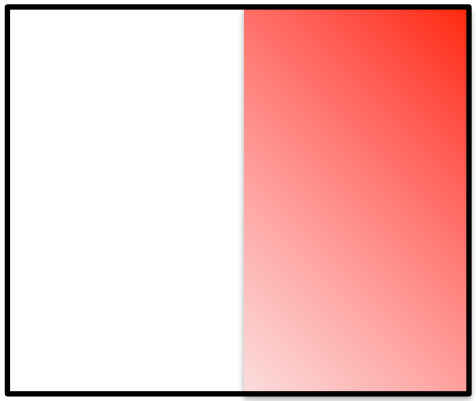
Random



Tradeoff



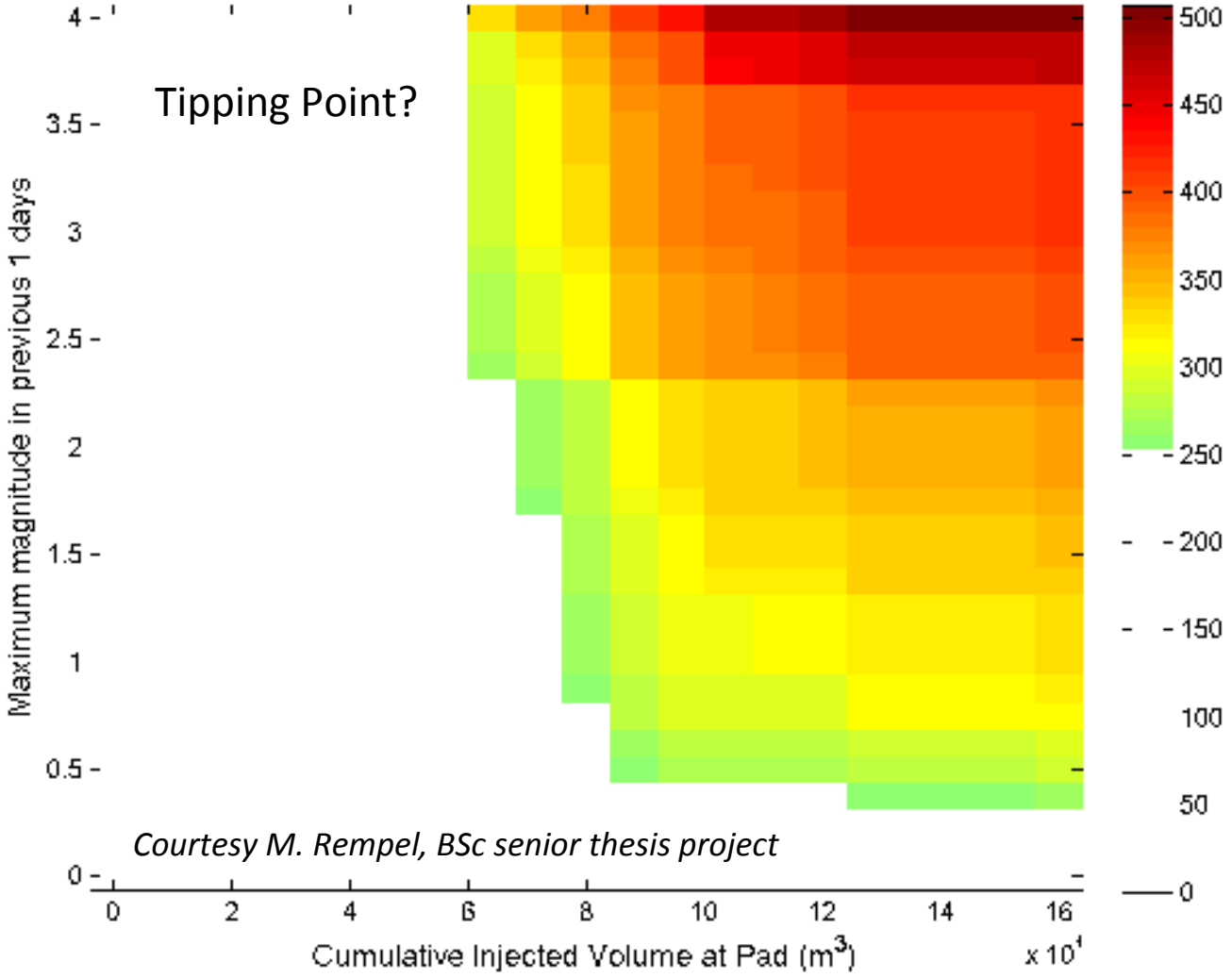
Operational Tipping Point



Activity Tipping Point

Northern Montney EHMs

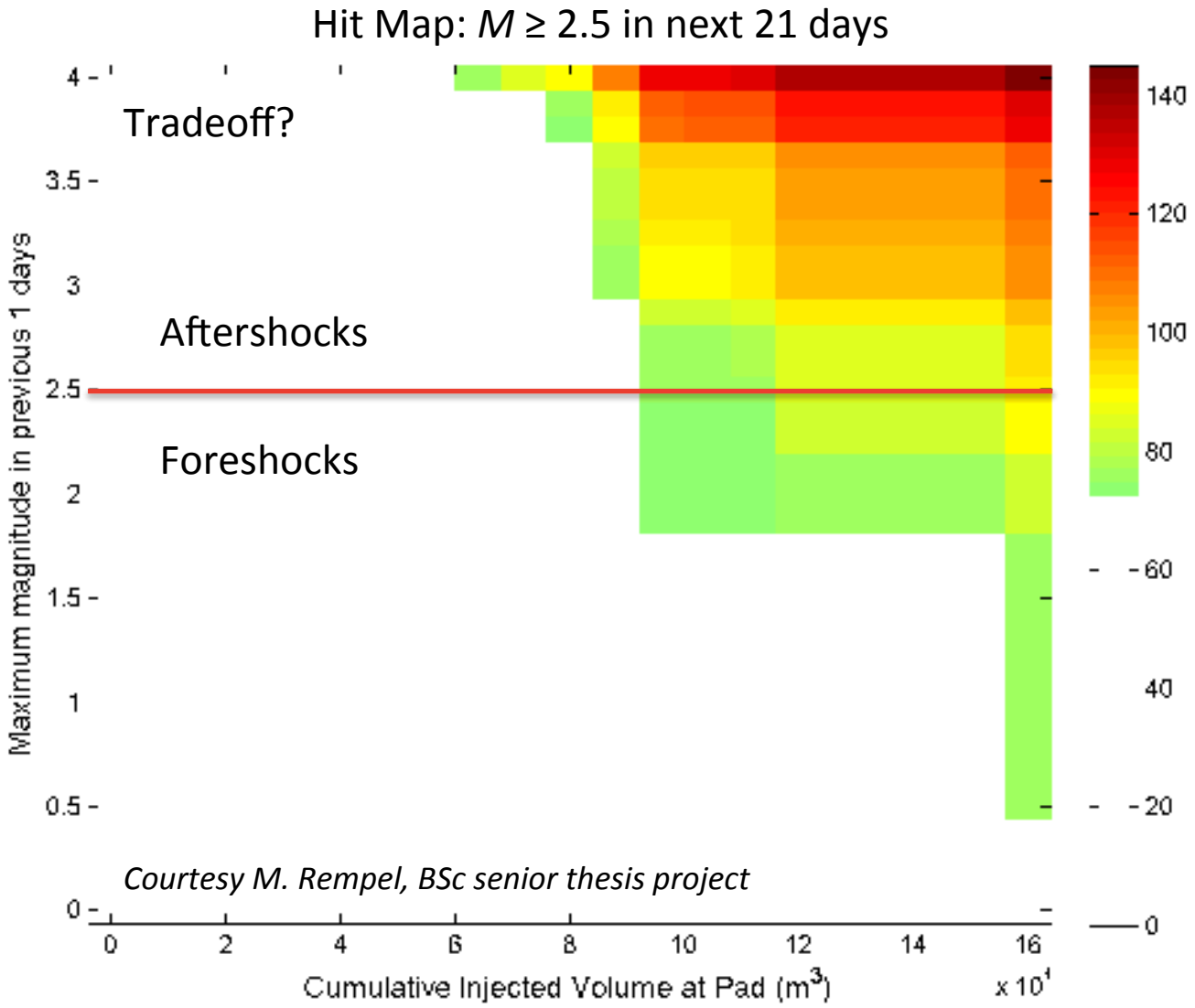
Hit Map: $M \geq 1$ in next 4 days



Courtesy M. Rempel, BSc senior thesis project

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

Northern Montney EHMs

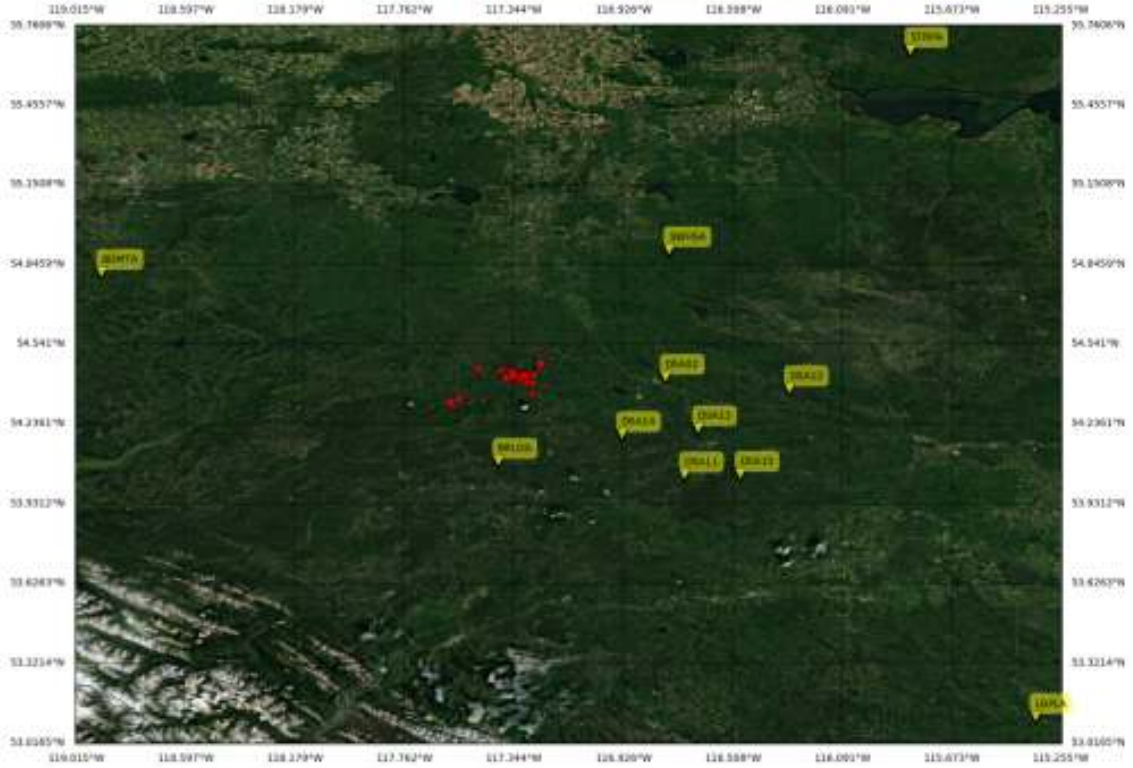


Courtesy M. Rempel, BSc senior thesis project

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



ObsPy
A Python Framework for Seismology

EQcorrscan
Correlation for earthquake detection in Python

See poster by Vragov and Eaton

Current Activities

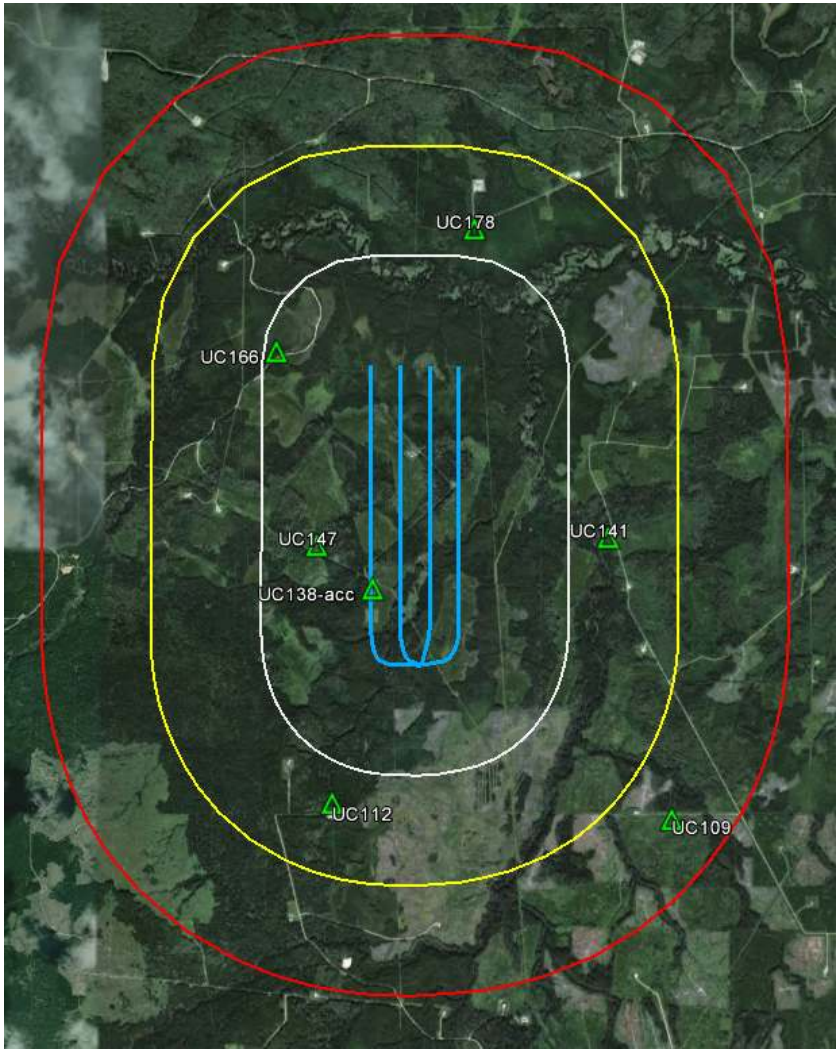


Image courtesy of Michael Laporte, Nanometrics

- 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

Acknowledgements

- Trans Alta, Nanometrics and NSERC (Induced Seismicity Processes CRD)
- Repsol, Nanometrics and Canadian Discovery Ltd. (data for *Science* paper)
- Noble Energy and Spectraseis (Marcellus Surface Microseismic Experiment)
- Chevron, ConocoPhillips, AquaTerra, Nanometrics (IRC)
- Ali Mahani (preprint of northern Montney BSSA paper)