Alberta Energy Regulator

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ALBERTA GEOLOGICAL SURVEY

Seismometers, Networks, & Induced Seismicity

Ryan Schultz

Overview

1) Seismometers & RAVEN.
2) Evaluating a network’s performance.
3) Induced seismicity near Fox Creek.

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Chapter 1:

Earthquake Monitoring and the Installation of RAVEN

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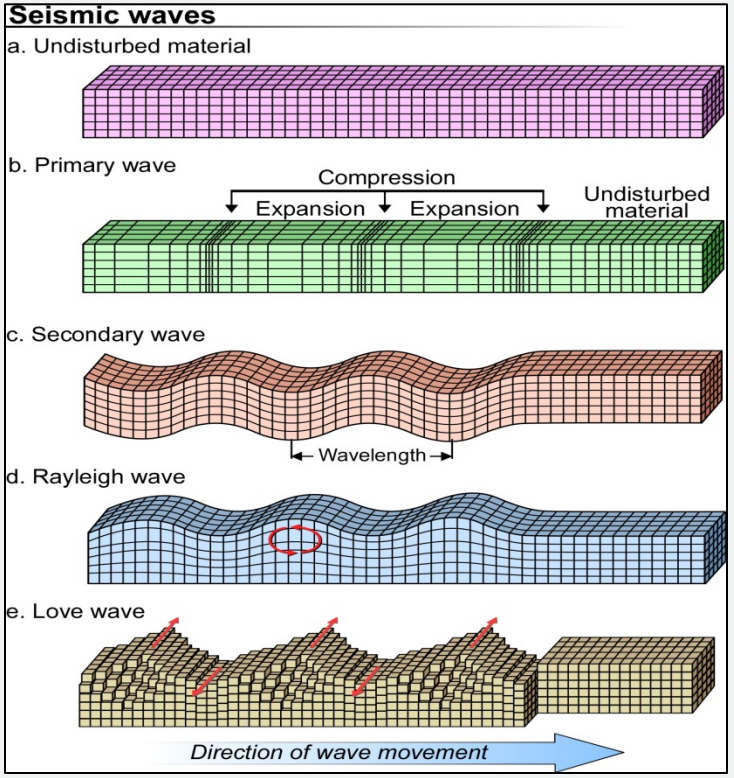
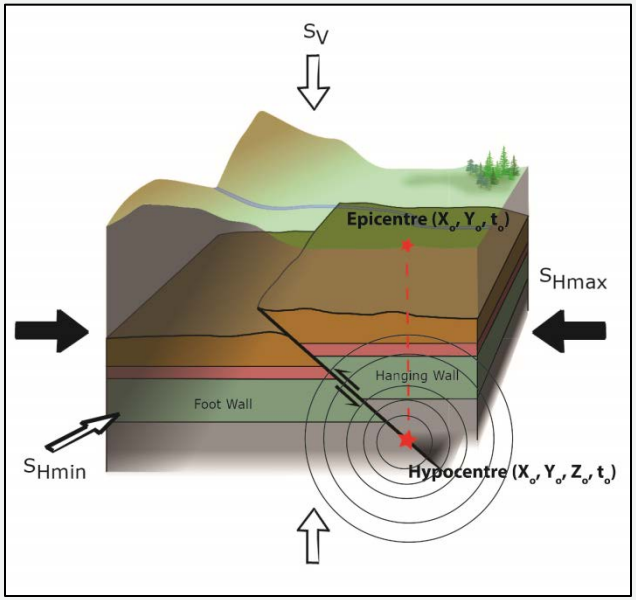
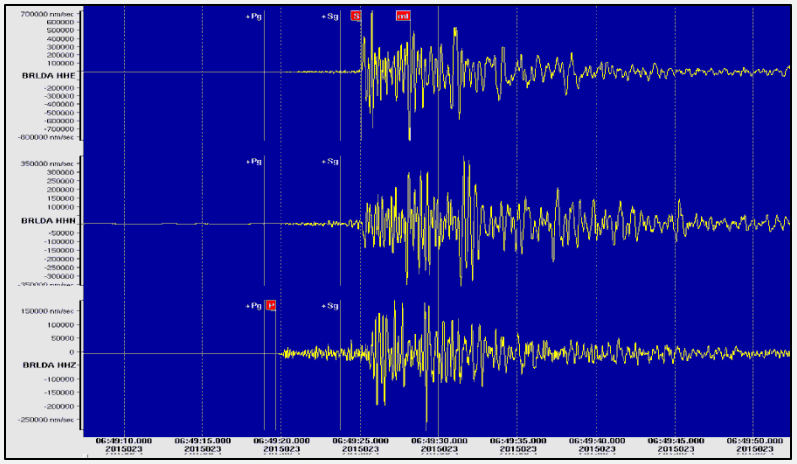
How do you Measure Ground Motion?

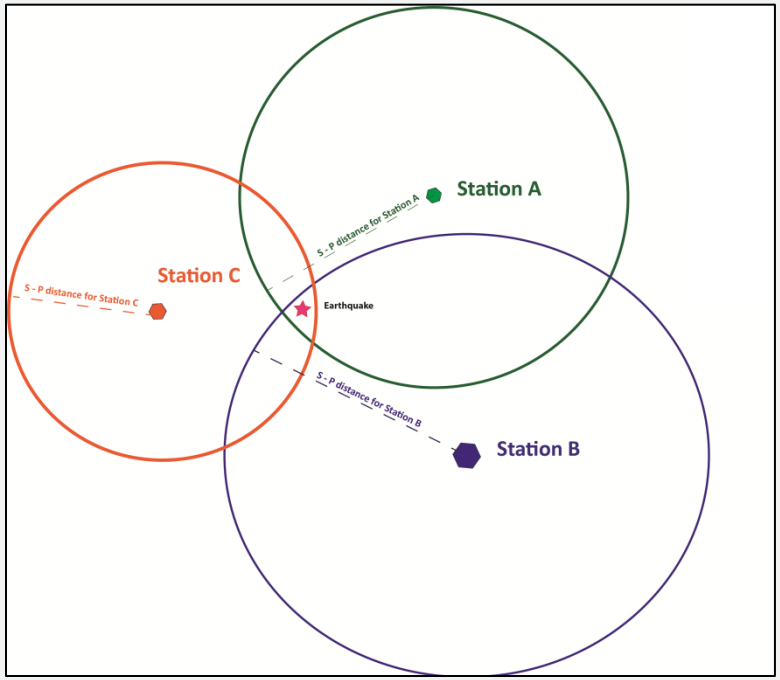


After AGS Website

How do you Measure Earthquakes?







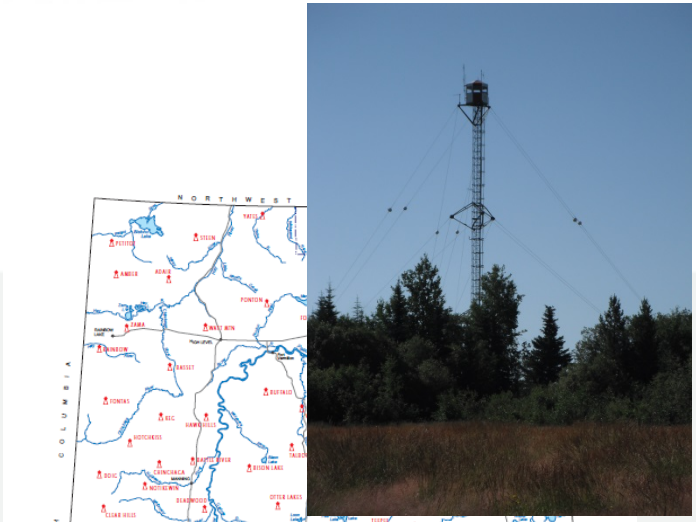
After AGS Website

Installation: Site Considerations

- Cultural noise: Day-to-day human activities have major impacts on performance.
- Natural noise: Flowing rivers, standing bodies of water, swaying trees, wind & pressure fluctuations.
- Vandalism: equipment is both fragile and expensive.
- Vault flooding: Equipment is water resistant, but flooding can impact performance.
- Ease of access: How hard is it to maintain the site?
- Clear view of sky for satellite telemetry.

Wildfire Towers

- Remote locations: few people means less noise, and less likely to have curious people bump into it.
- Towers have operator on site and are under lock & key.
- Chosen sites have road access
- Other sites are placed on private land in locations where there are no fire towers.



Site Installation P1: Infrastructure

Dig Holes

Bury vaults in them

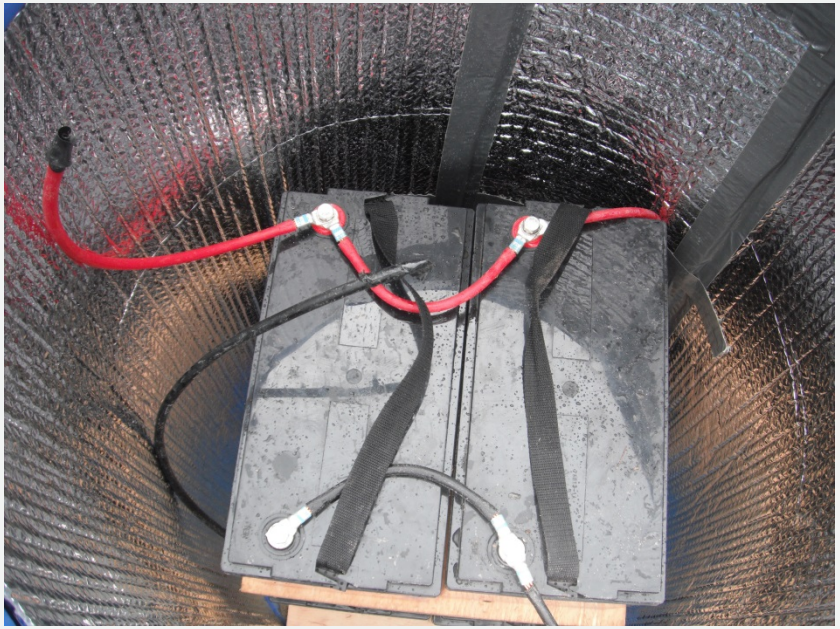
Site Installation P1: Infrastructure

Make Cement Pier for Seismometer

Fence Off Enclosure

Site Installation P2: Electronics

Wire Up Four Batteries



Mount/Align Solar & Satellite

Site Installation P2: Electronics

Setup Electronics

Align Seismometer

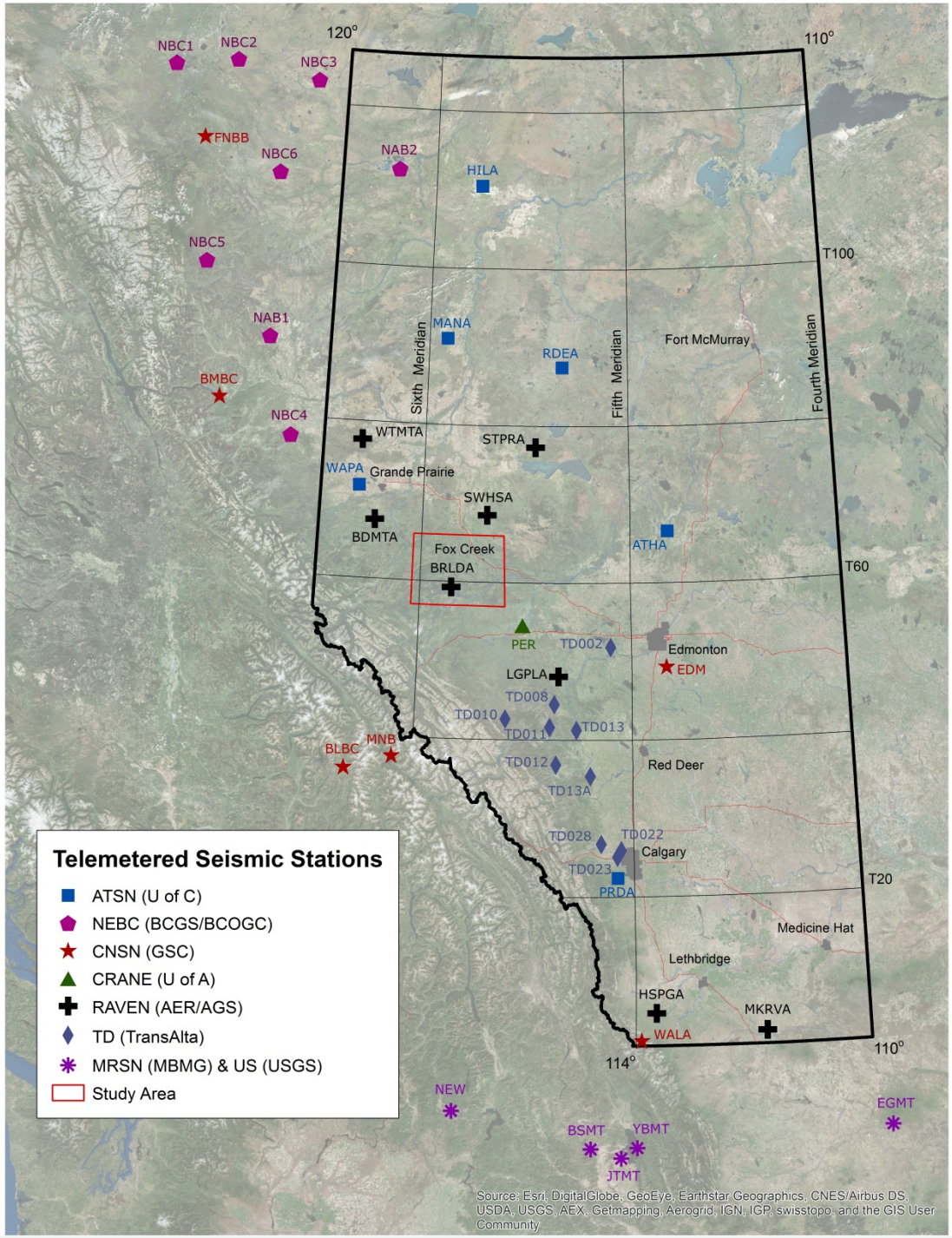
Not pictured: Gordon Jean & Rob Natyshen

RAVEN Station Installations


Nanometrics
Passive Seismic Station

Increased Station Density

- Contributions from multiple agencies.
- New stations from AGS, NRCan, Western, UofA, UofC, & McGill contributions.
- See also: Schultz & Stern 2015, IRIS RV, & AGS OFRs.



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Chapter 2:

Detection threshold and location resolution of the Alberta Geological Survey catalogue

Ryan Schultz, Virginia Stern, Yu J. Gu, David Eaton

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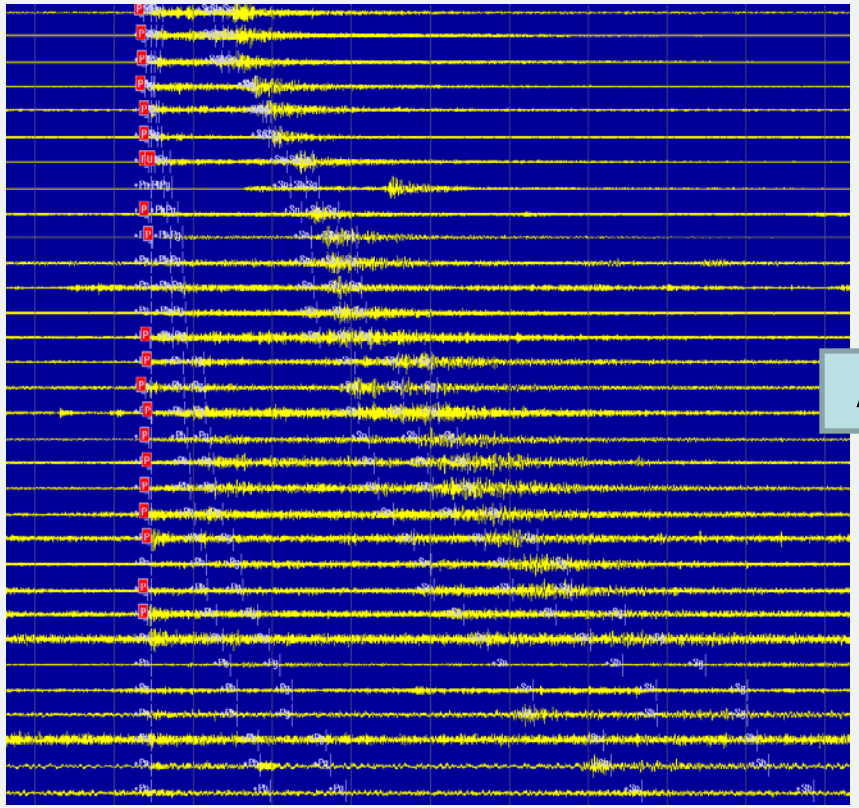
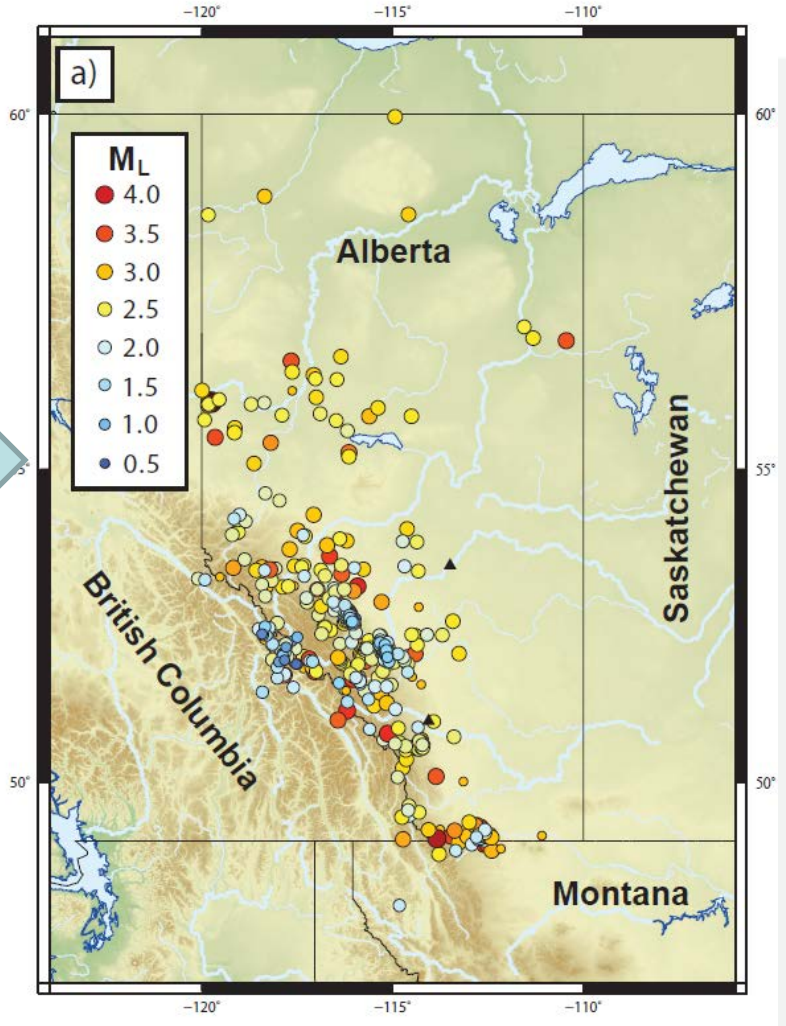
Raw Waveform Data



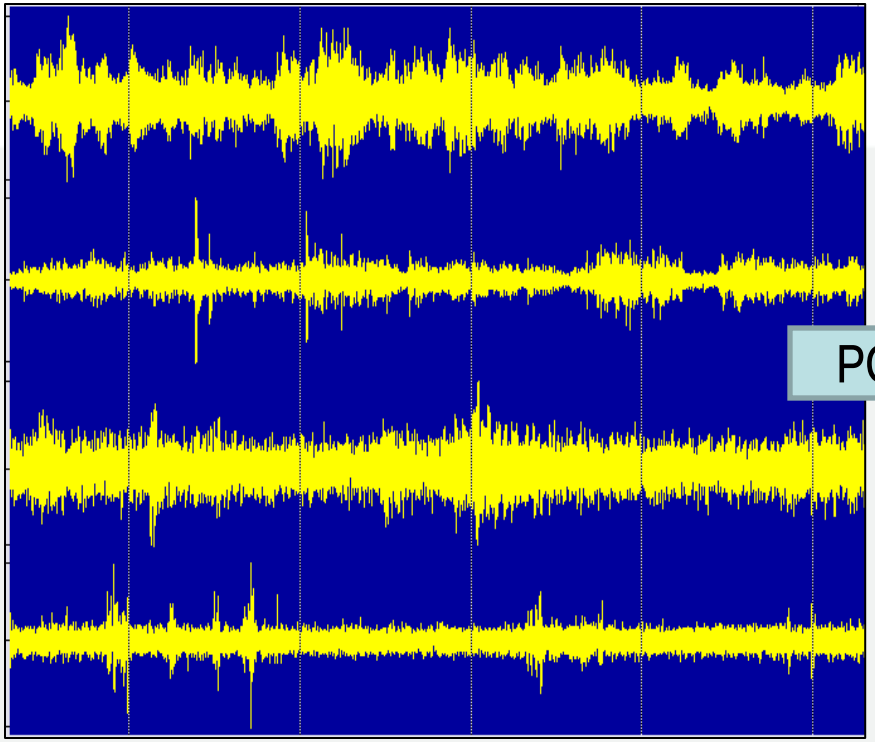
Antelope

Earthquake Catalogue



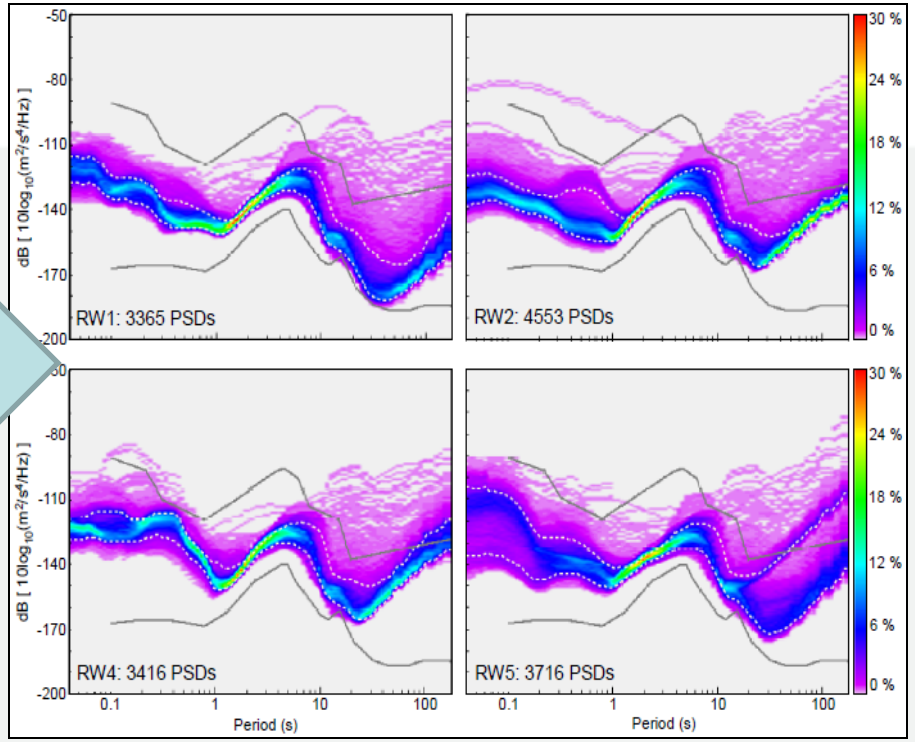
How well does the catalogue perform?

Ambient Station Noise

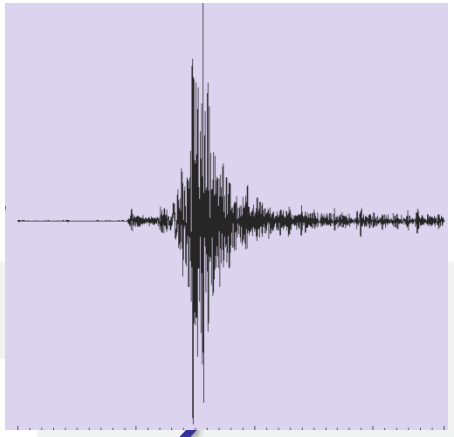


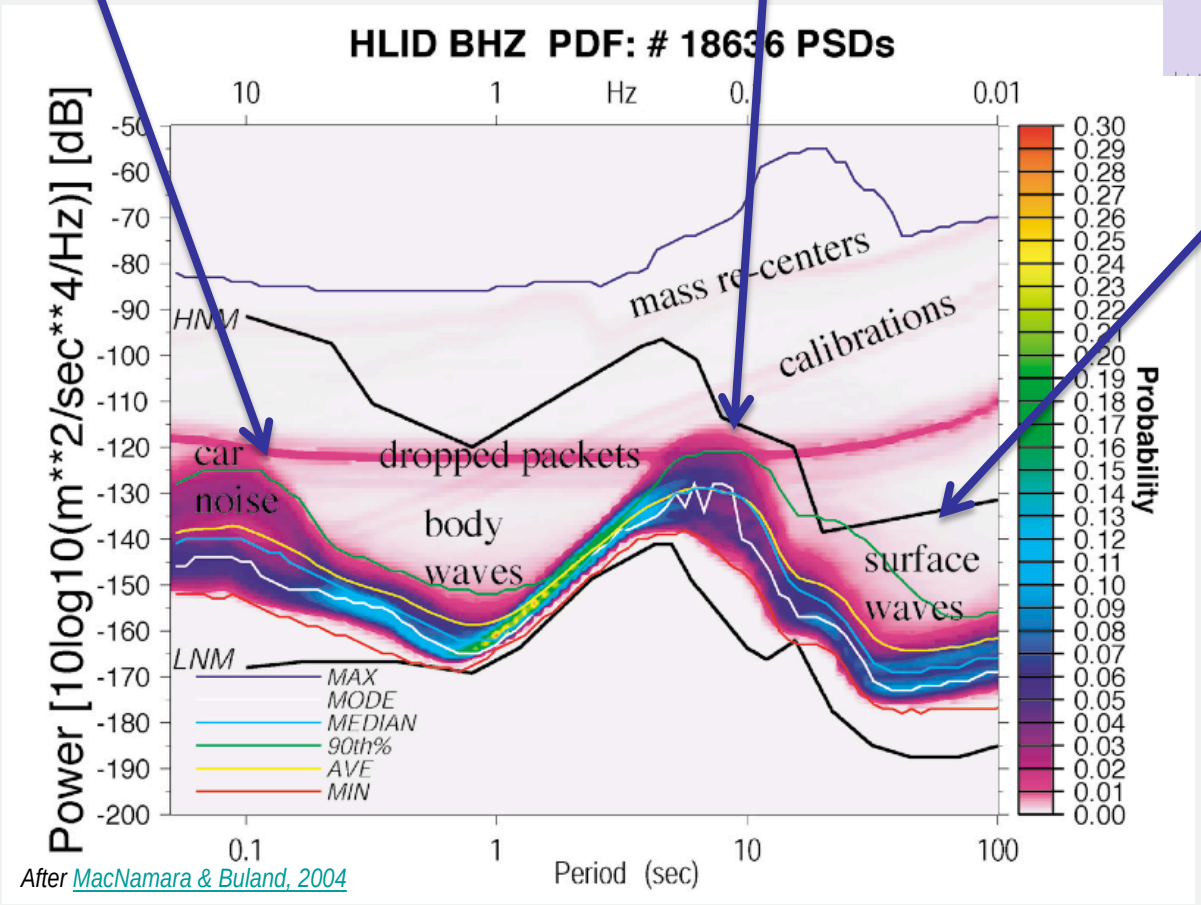
PQLX

Probability Density Function



- Continuous waveform data segmented into hours.
- Years of time series data compiled.
- Transformed to frequency domain.
- Spectrums are analyzed as a statistical distribution.





After [MacNamara & Buland, 2004]

- Various sources of noise:

  Cultural, Wind, Tide, Diurnal,

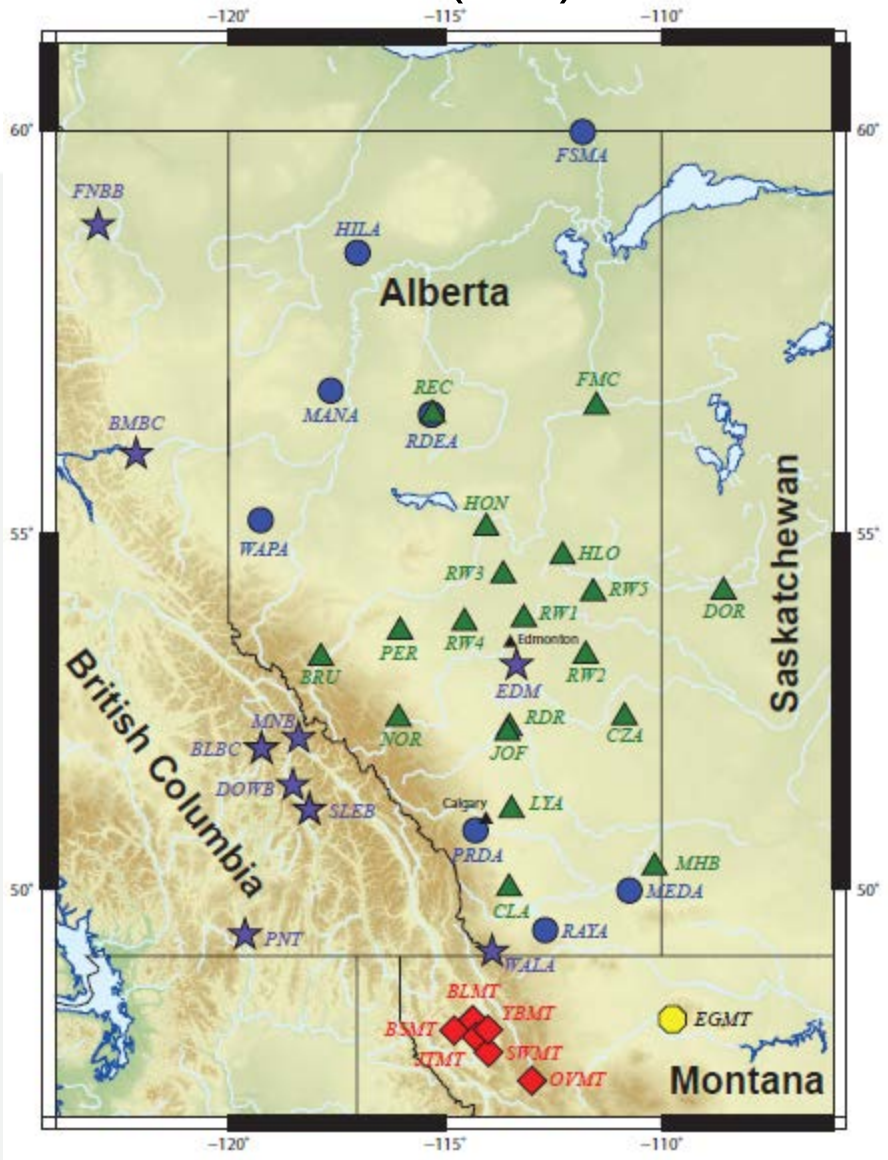
  Seasonal.

- PDFs can be compared to

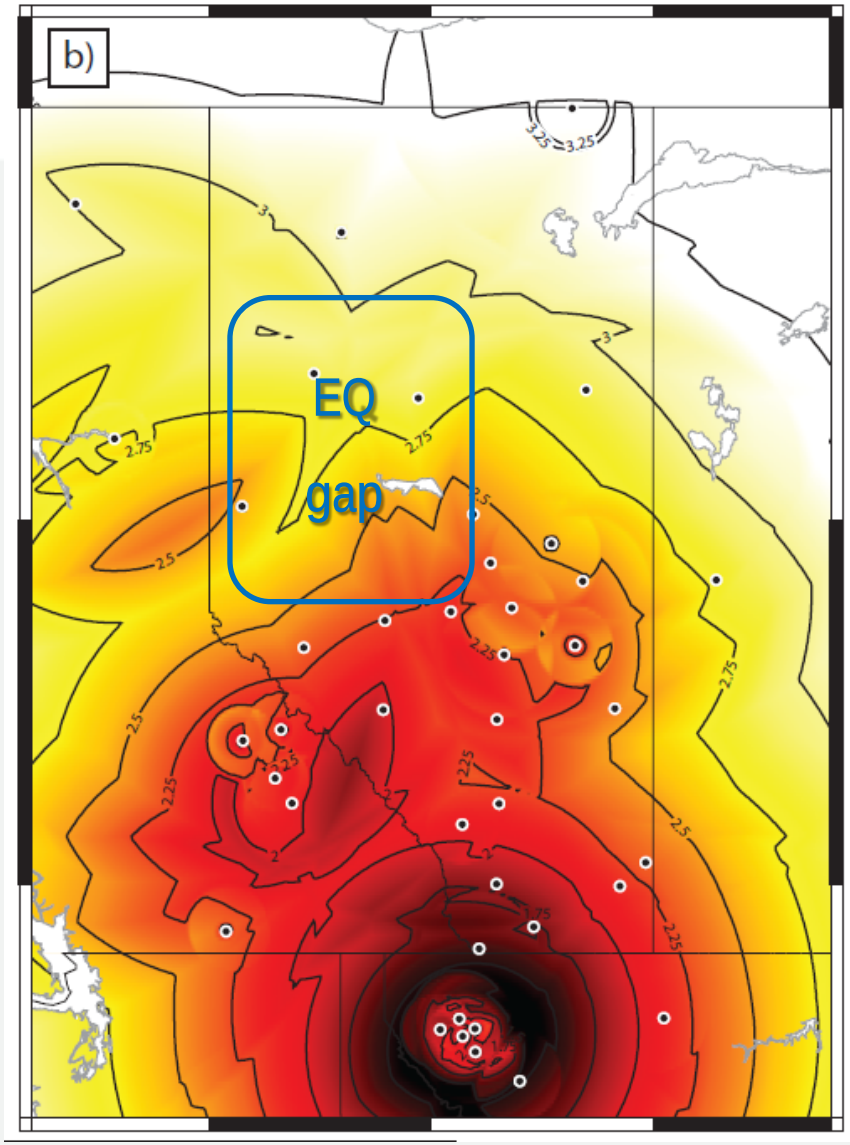
  known spectrums of an

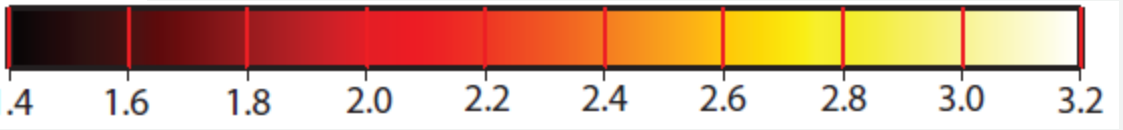
  earthquake.

Stations (2012)



Magnitude of Completeness





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Summary

- **Noise at stations can be characterized to understand their performance individually, and how they change with time (days, seasons, years)**
- **Combined with simulation of earthquake spectrum, we can determine the smallest magnitude events that the network completely captures.**
- **This allows us to aim where new stations are needed the most.**

Reference:
Schultz, R., Stern, V., Gu, Y.J., Eaton, D. (2014) Detection threshold and location resolution of the Alberta Geological Survey catalogue. *Seismol. Res. Lett.*, 86(2A), 385-397, doi: 10.1785/0220140203.

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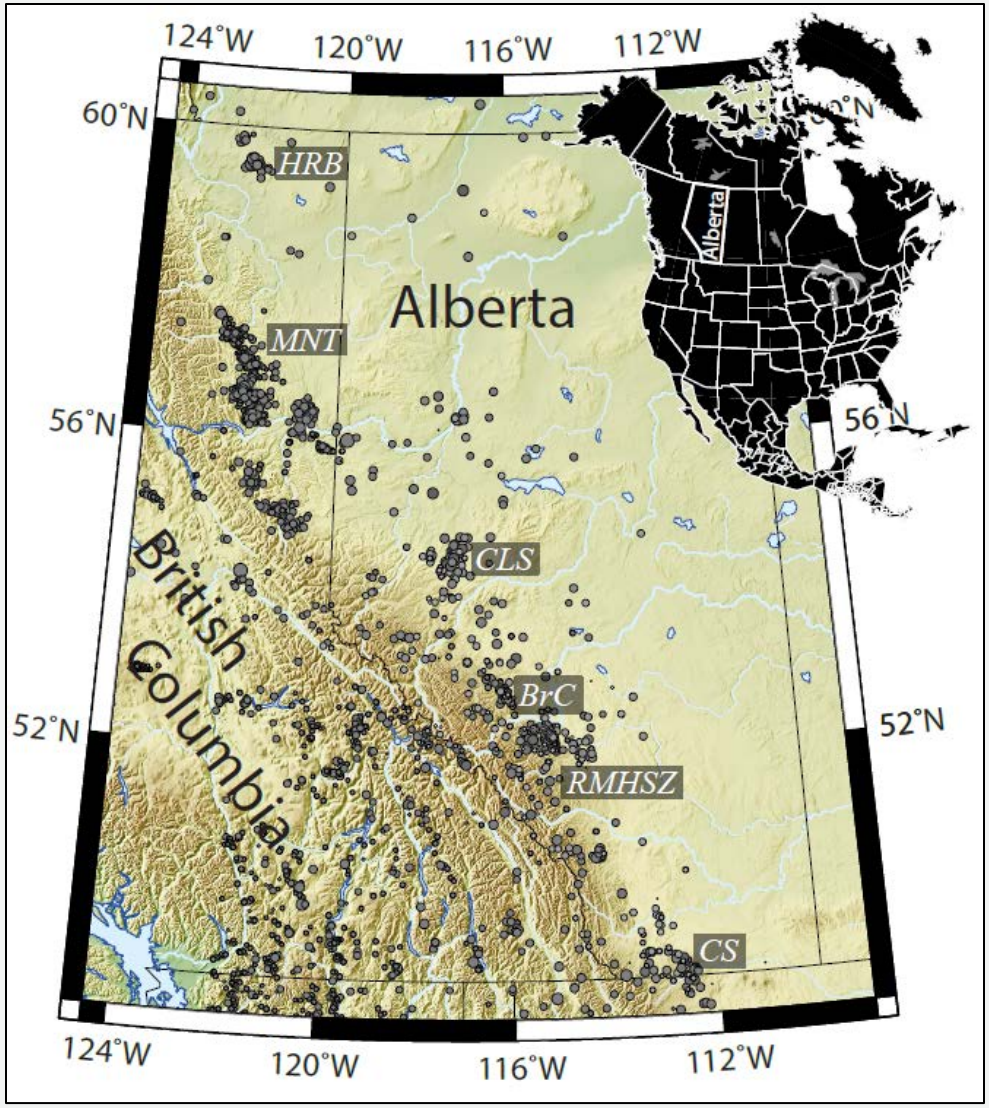
Chapter 3:

A Seismological Overview of the Induced Earthquakes in the Duvernay Play near Fox Creek, Alberta

Ryan Schultz, Ruijia Wang, Yu Jeffrey Gu, Kristine Haug, Gail Atkinson

Seismicity in the WCSB

- Seismicity in the WCSB is sparse and relatively quiescent.
- Long-lasting clusters have been recognized.
- Three clusters account for the majority of Albertan seismicity: RMHSZ, BrC, CLS.



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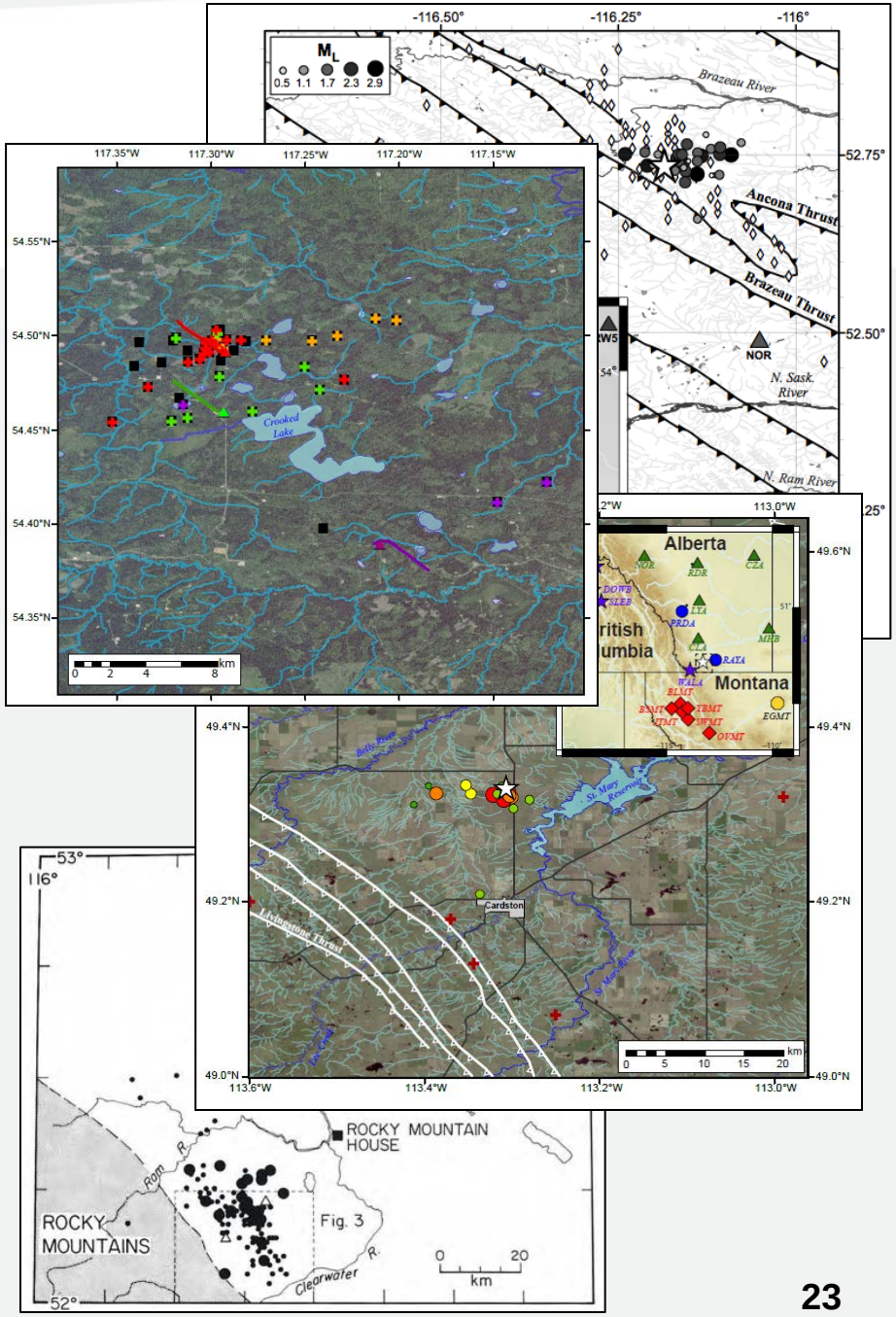
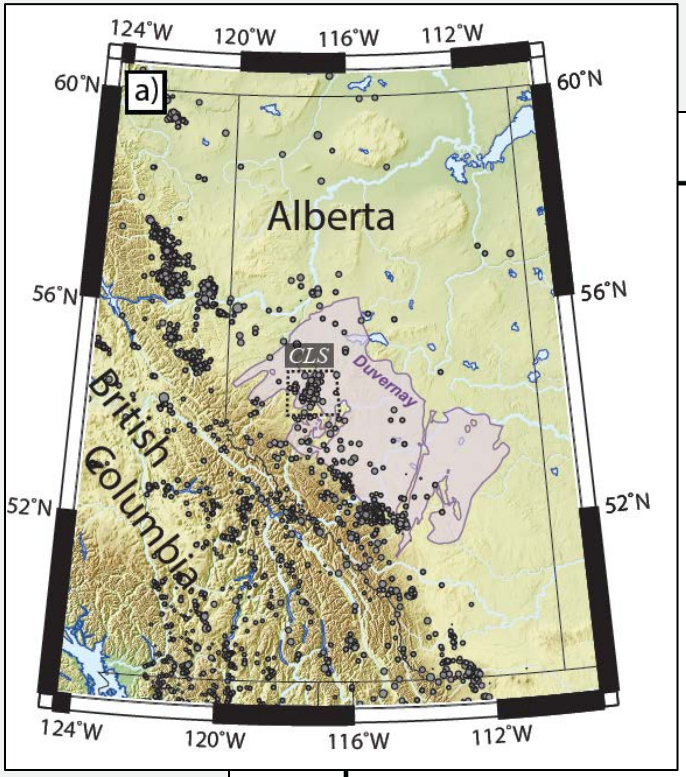
Induced Clusters

- Majority of earthquake clusters have been linked with petroleum resource development.
- RMHSZ associated with conventional gas production [Baranova et al., 1999].
- Brazeau cluster (Cordel Field) linked to waste-water disposal [Schultz et al., 2014].
- Cardston swarm associated with hydraulic fracturing [Schultz et al., 2015b].



The Earthquakes Near Fox Creek

- Related to hydraulic fracturing operations in the Duvernay Formation [Schultz et al., 2015a].
- Obvious change in the rate of EQs in the region, even after network biases are removed.



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The Earthquakes Near Fox Creek

- Obvious change in the rate of EQs in the region, even after network biases are removed.
- Even a few larger earthquakes (4 Mw) have been felt in nearby town of Fox Creek [Yenier et al., 2017].
- MMI of II-III in Fox Creek is consistent with felt reports.
- Jan 23 2015 3.8 Mw event prompted TLP.

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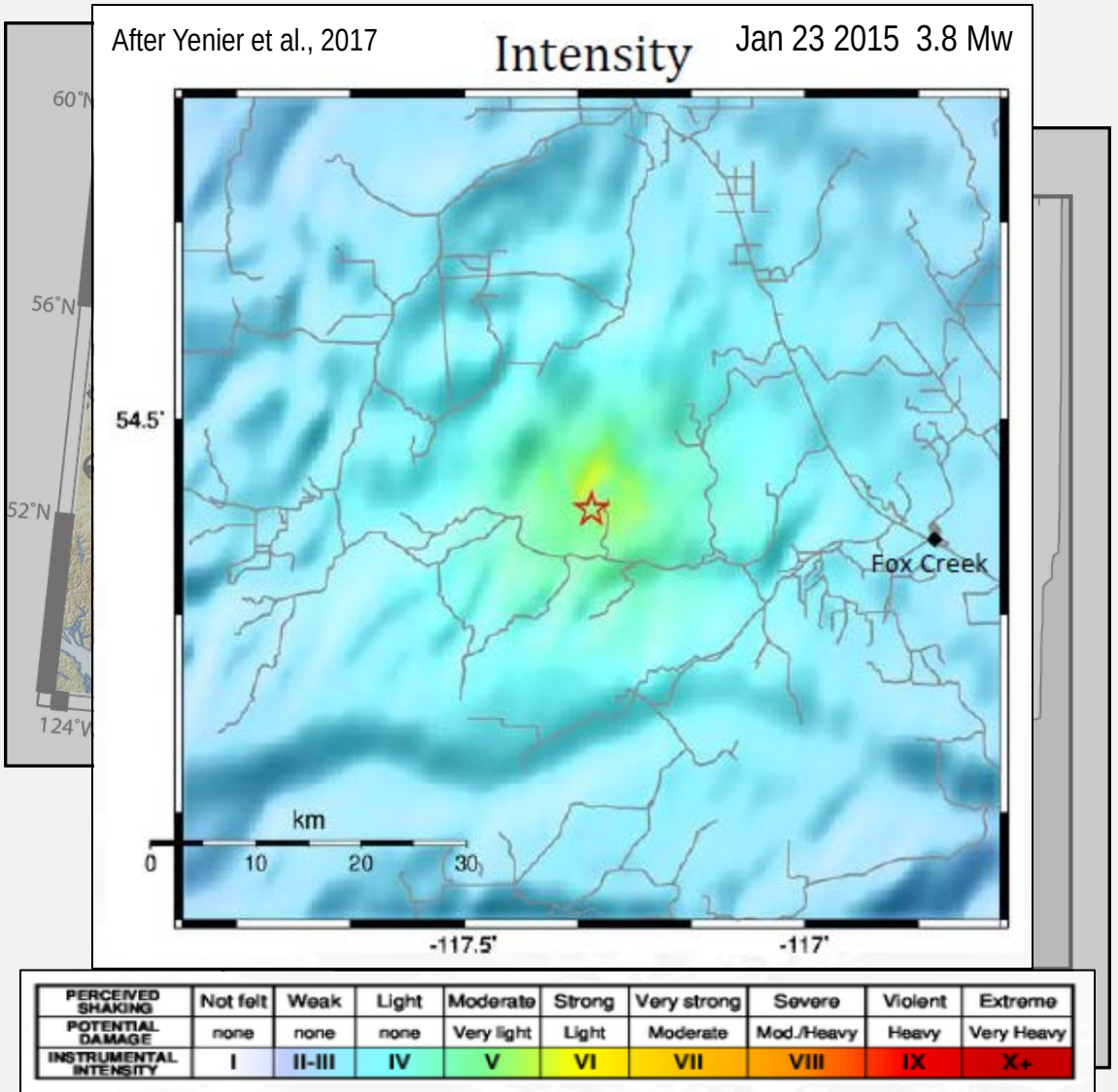
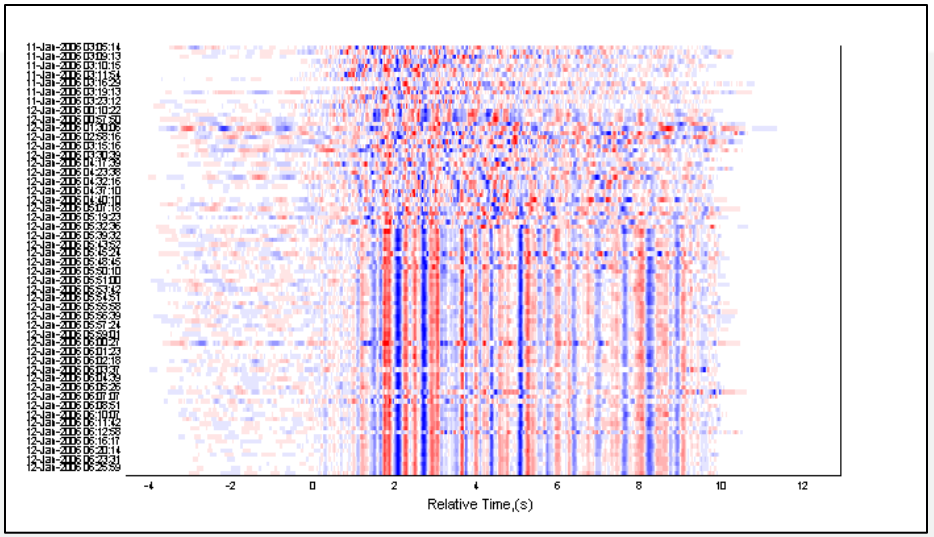
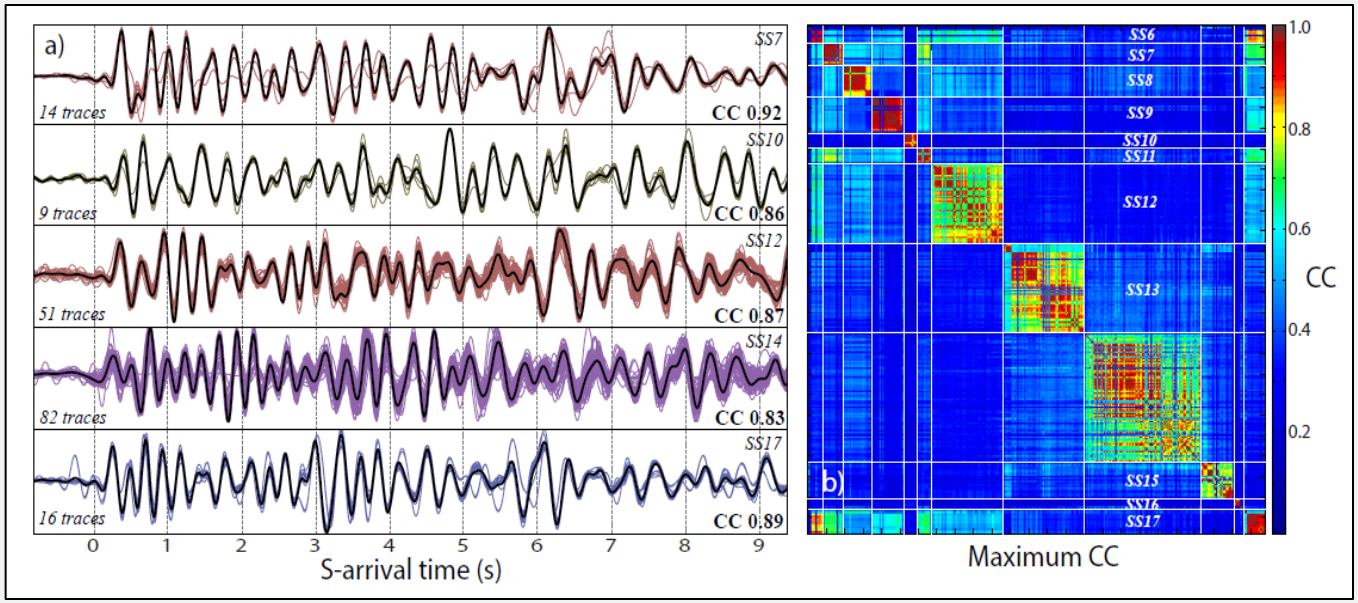


Waveform Multiplicity

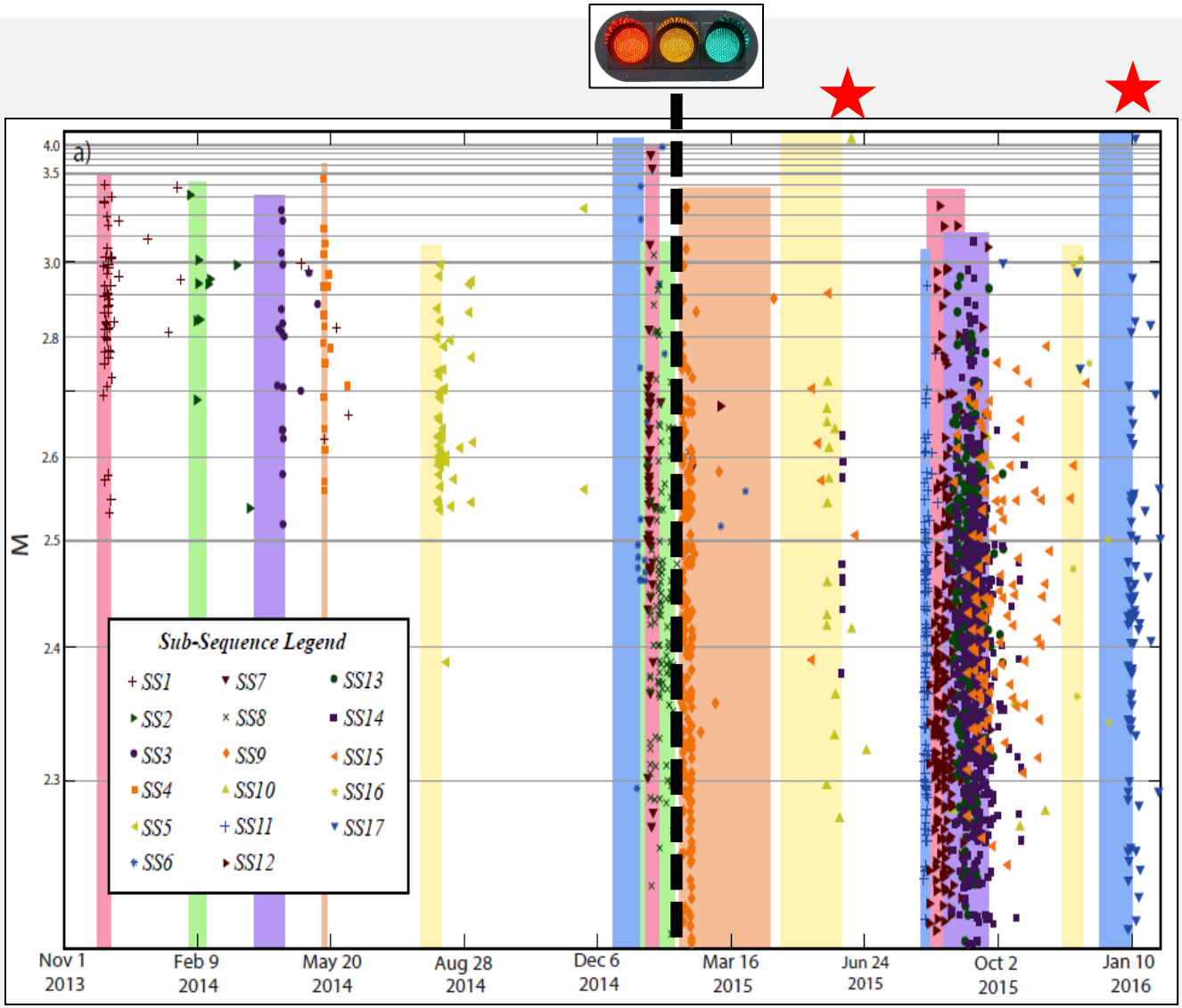
- Events at the CLS continue to be repeating EQs.
- 17+ clusters identified in this fashion.
- Distinguishable waveform implies distinct mechanism/locations.
- Event cluster are chronologically sorted…





Waveform Cross-Correlation Search

- Use repeating EQs as templates in MFA.
- Allows for lowering of Mc by up to 1 Mw.
- Detect small magnitude events, x4 catalogue size (~2000).



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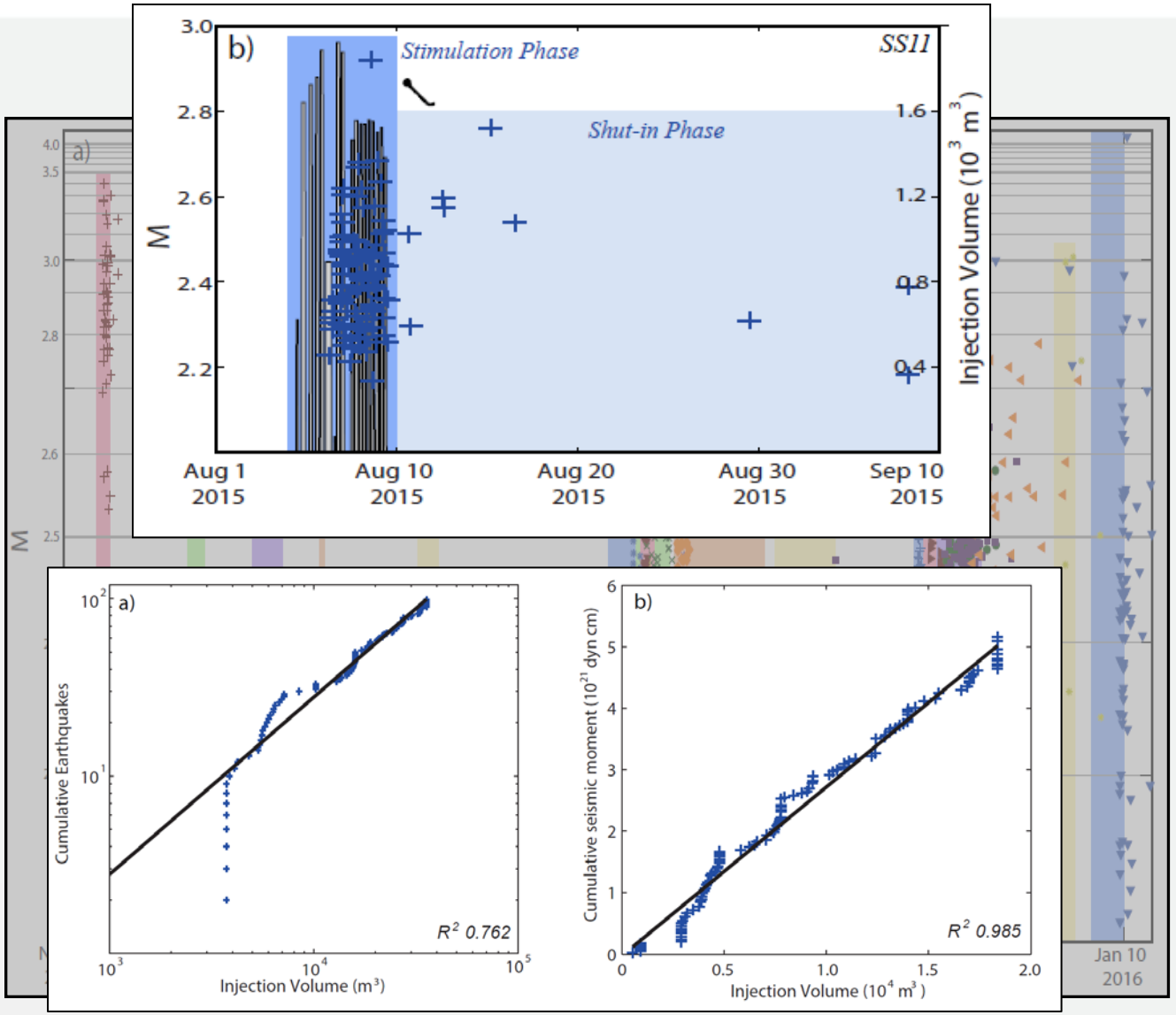
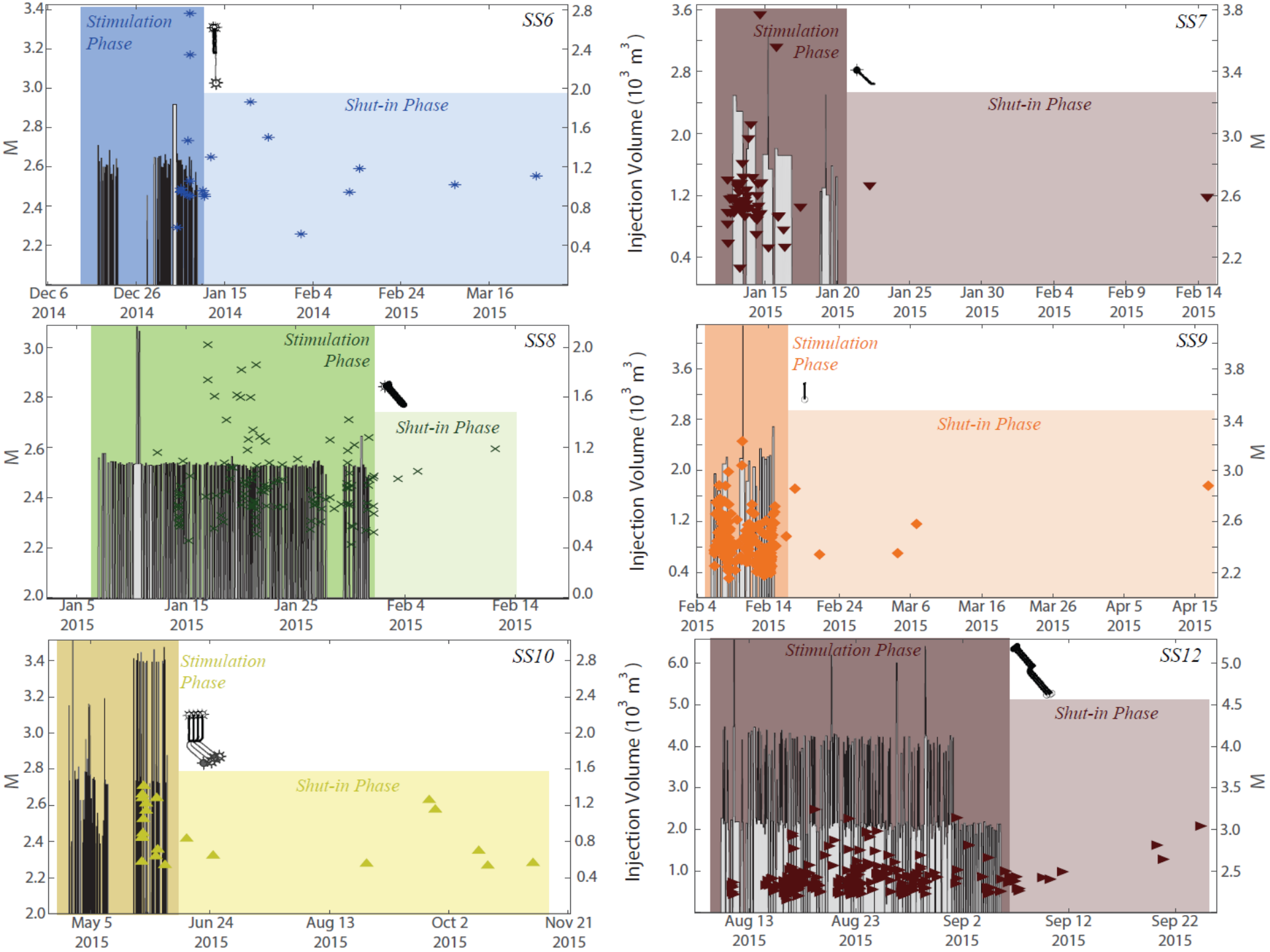
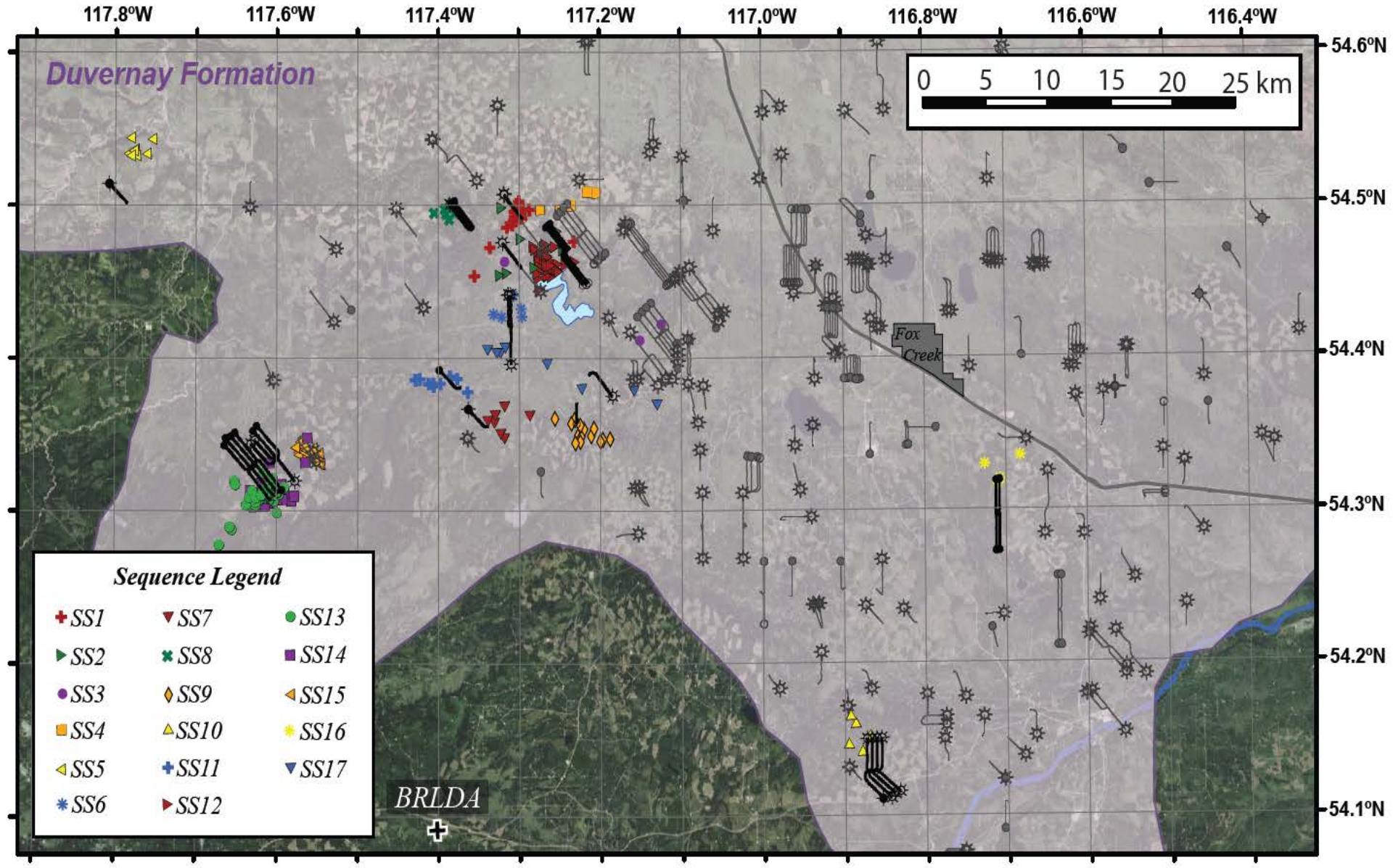
Spatiotemporal Association with HF

- Detect small events, x4 catalogue size (~2000).
- Clusters correlated with completions.
- EQs happen in two phases: stimulation phase is high rate, shut-in phase is lower rate.

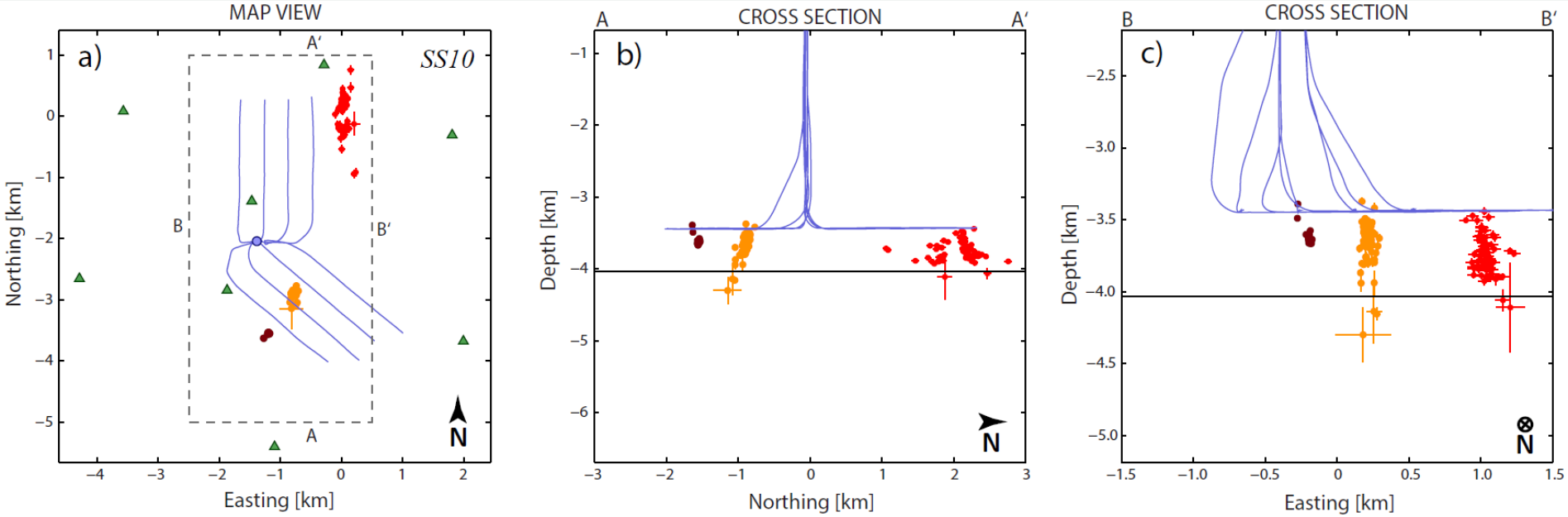



SS6
Stimulation Phase
Shut-in Phase
M
Dec 6 2014
Dec 26 2014
Jan 15 2014
Feb 4 2014
Feb 24 2015
Mar 16 2015
SS7
Stimulation Phase
Shut-in Phase
Injection Volume (10^3 m^3)
M
Jan 15 2015
Jan 20 2015
Jan 25 2015
Jan 30 2015
Feb 4 2015
Feb 9 2015
Feb 14 2015
SS8
Stimulation Phase
Shut-in Phase
M
Jan 5 2015
Jan 15 2015
Jan 25 2015
Feb 4 2015
Feb 14 2015
SS9
Stimulation Phase
Shut-in Phase
Injection Volume (10^3 m^3)
M
Feb 4 2015
Feb 14 2015
Feb 24 2015
Mar 6 2015
Mar 16 2015
Mar 26 2015
Apr 5 2015
Apr 15 2015
SS10
Stimulation Phase
Shut-in Phase
M
May 5 2015
Jun 24 2015
Aug 13 2015
Oct 2 2015
Nov 21 2015
SS12
Stimulation Phase
Shut-in Phase
Injection Volume (10^3 m^3)
M
Aug 13 2015
Aug 23 2015
Sep 2 2015
Sep 12 2015
Sep 22 2015


Duvernay Formation
117.8°W
117.6°W
117.4°W
117.2°W
117.0°W
116.8°W
116.6°W
116.4°W
54.6°N
54.5°N
54.4°N
54.3°N
54.2°N
54.1°N
0 5 10 15 20 25 km
Fox Creek
BRLDA
Sequence Legend
SS1
SS2
SS3
SS4
SS5
SS6
SS7
SS8
SS9
SS10
SS11
SS12
SS13
SS14
SS15
SS16
SS17

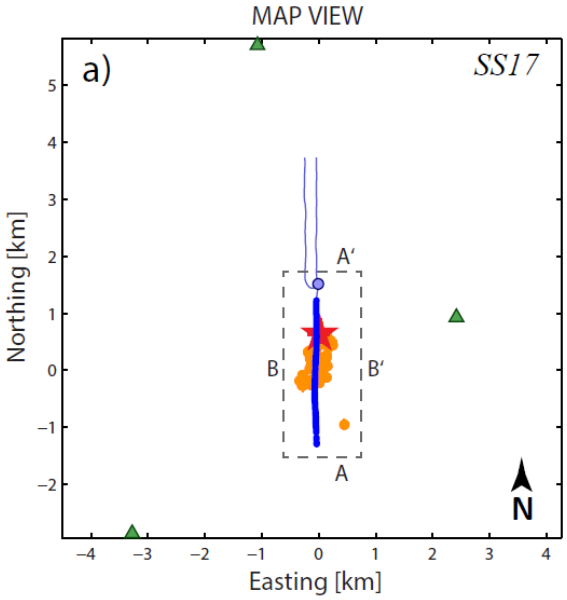
June 23 2015 TLP Red-light (*SS10*)

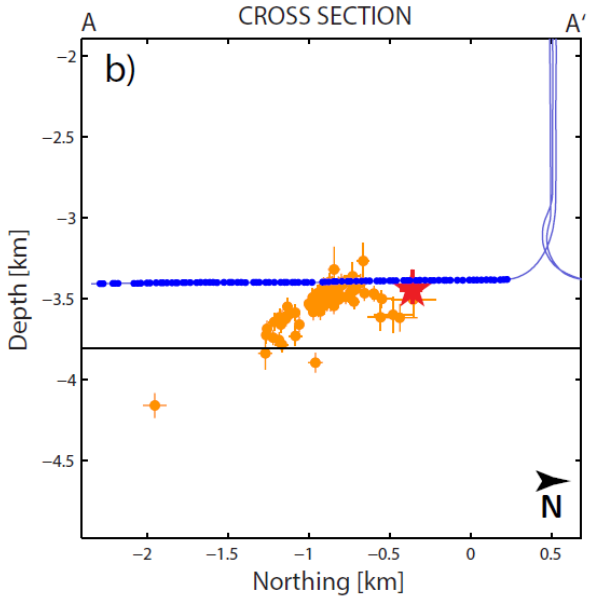
- Local array stations in **green**, well trajectories in **blue**, EQs in **reds**.
- 8 stations in roughly a circle and less than 3 km from well surface location.
- Clusters trend N-S with subvertical dip angles.
- Depths from Duvernay to basement.

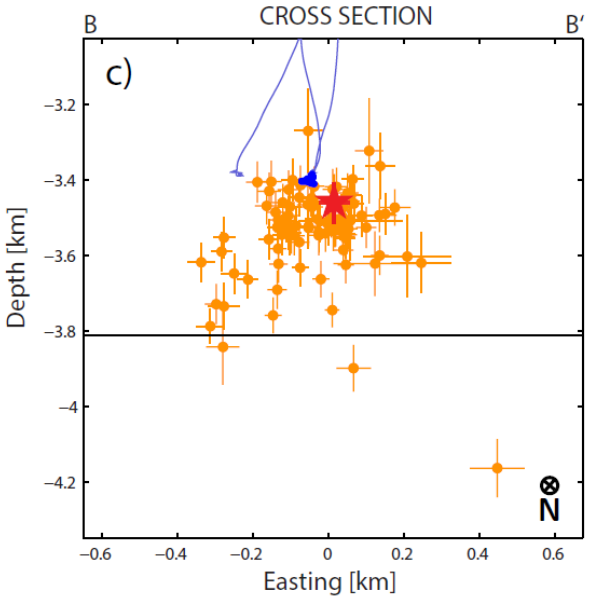


Jan 12 2016 TLP Red-light (*SS17*)

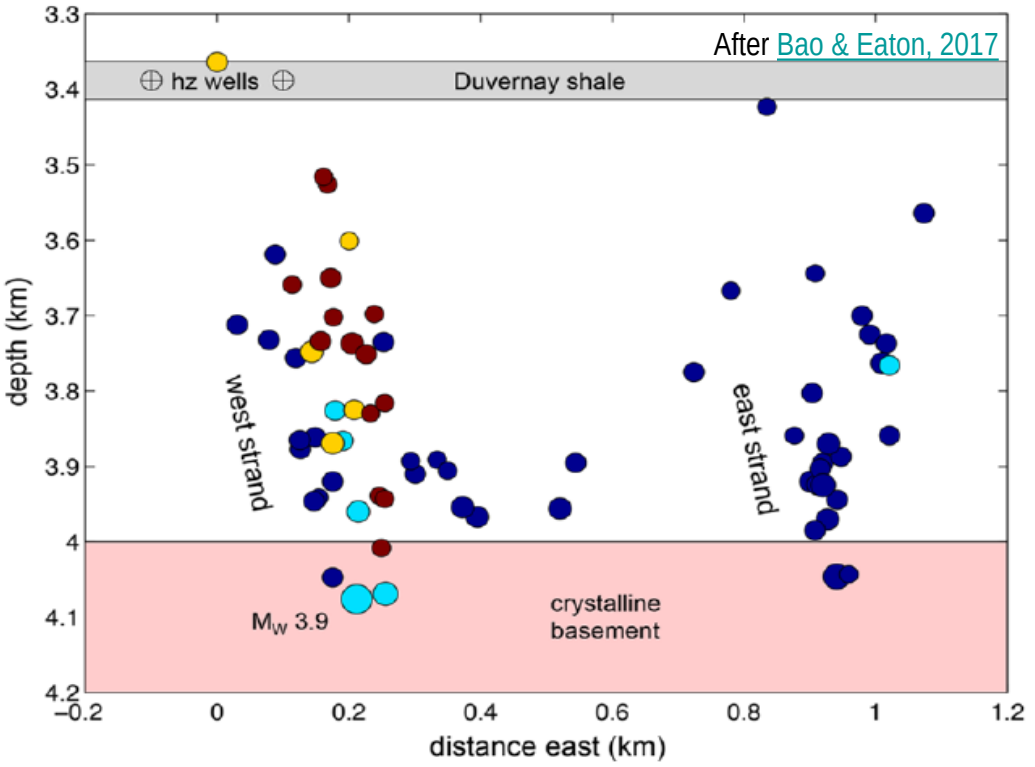
- Local array stations in **green**, well trajectories in **blue**, EQs in **orange**.
- 4 stations in lightning bolt shape up to 8 km from well surface location.
- Clusters trend N-S with subvertical dip angles.
- Depths from Duvernay to basement.

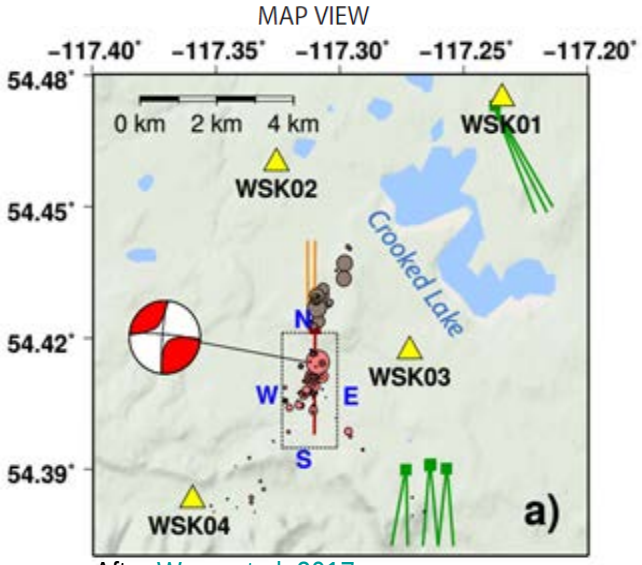




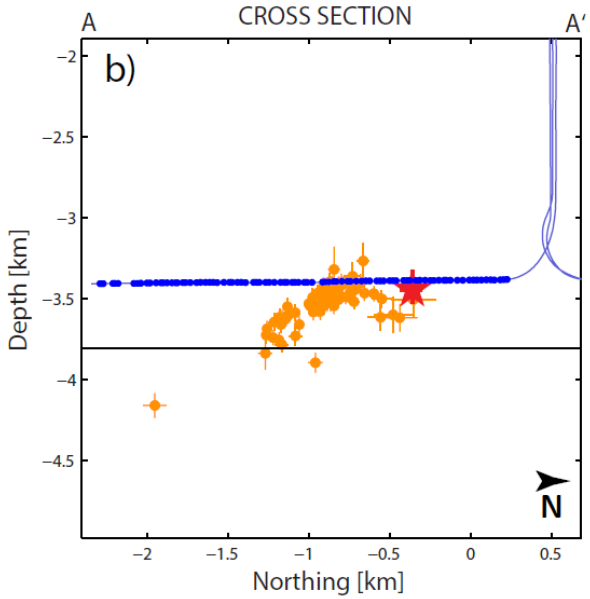


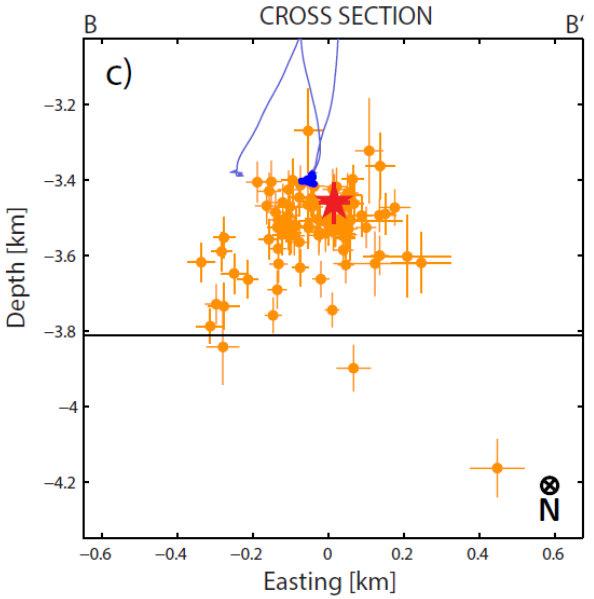
- **Consistency with results ~1 year earlier, northern half of completion** [Bao & Eaton, 2016].





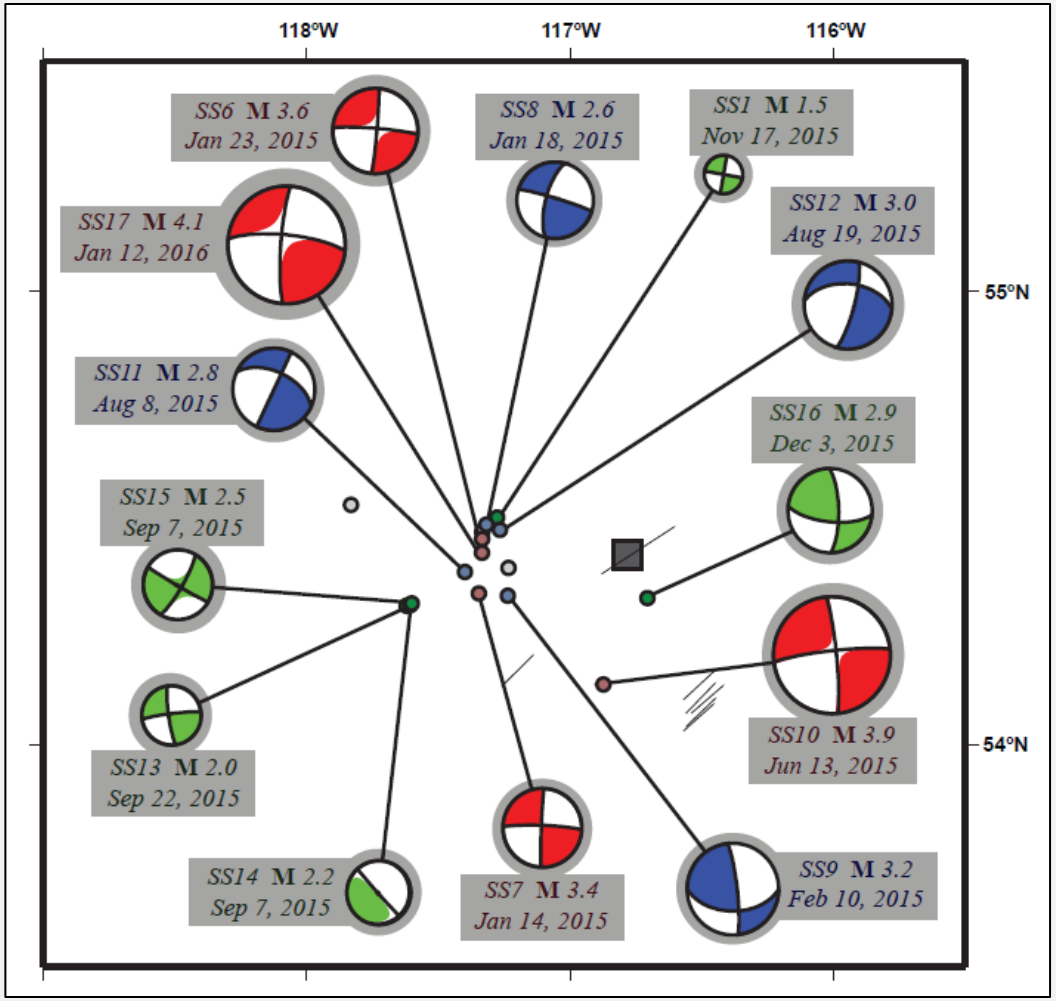
After Wang et al, 2017





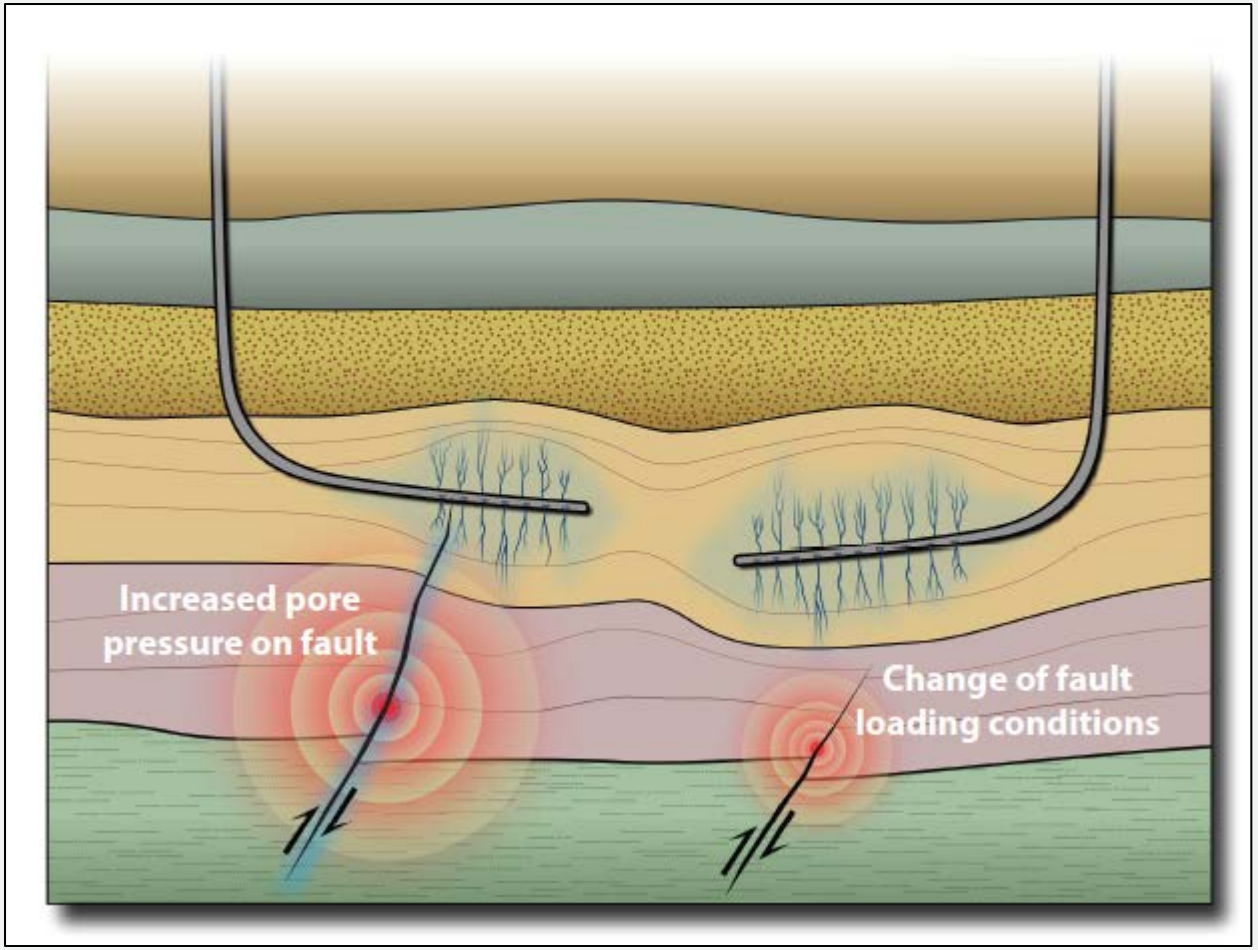
Moment Tensor Results

- Stacked EQ multiplets increases SNR.
- DC sources, agrees with Sh-max (~50°), agrees with stress regime (SS).
- **RED** full waveform inversion.
- **BLUE** double couple grid search.
- **GREEN** industry donated data.
- Orientations agree with DD: subvertical & ~N-S.



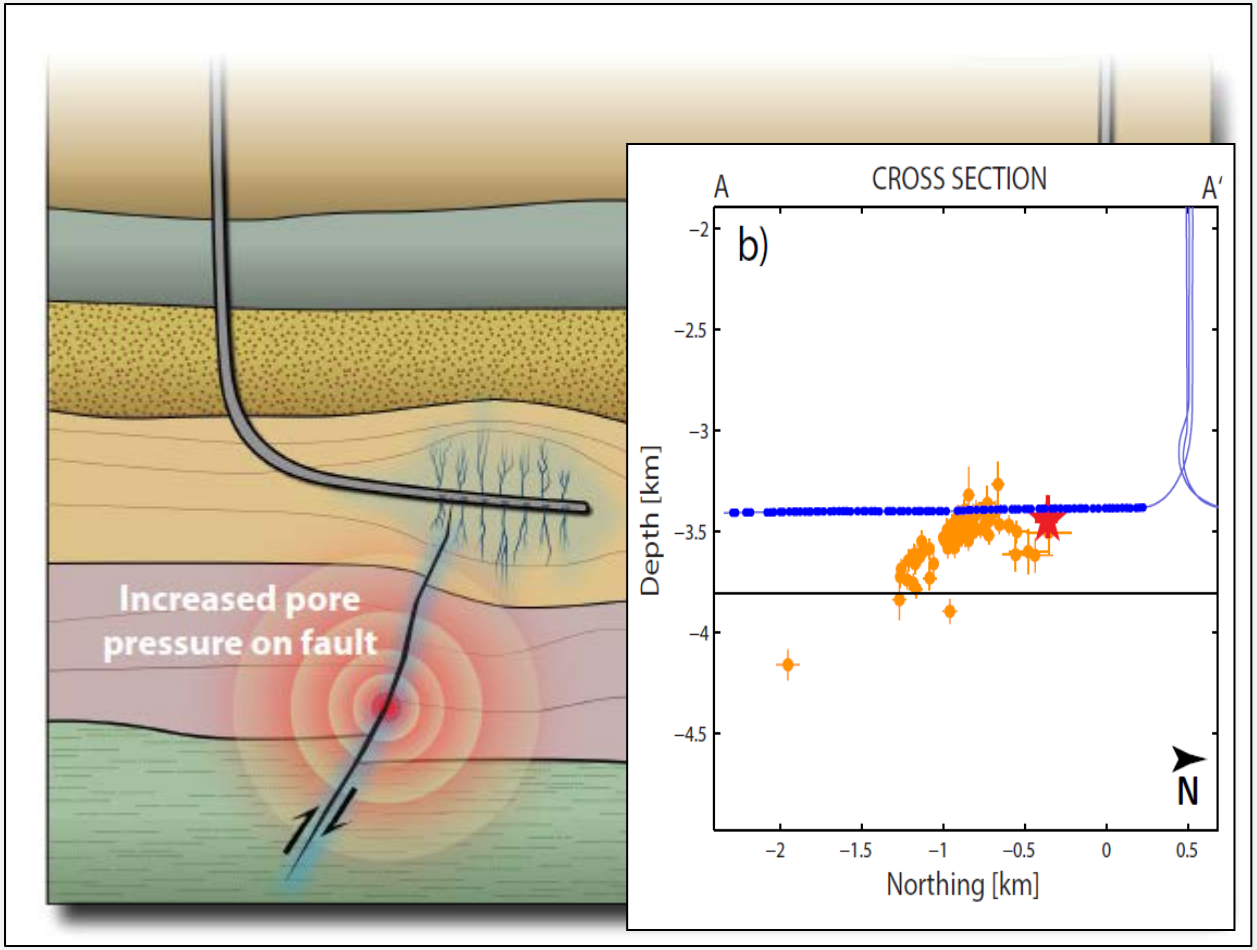
Implications

- EQ triggering is either the result of increased pressure on fault, or poroelastic stress transmission.



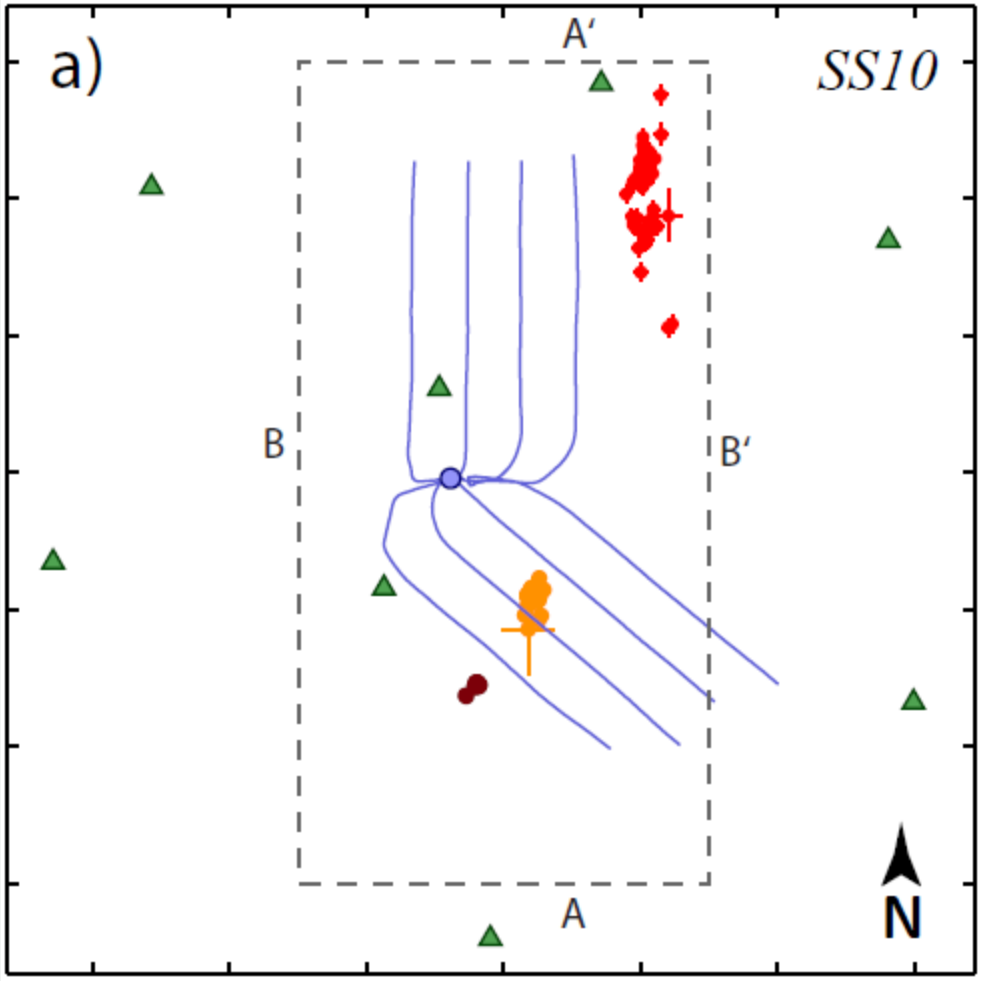
Implications

- EQ triggering is either the result of increased pressure on fault, or poroelastic stress transmission.
- Seismological observation appears to favour pore pressure mechanisms: directly imaged hydraulic communication & repeating EQs indicate slip in overpressured, low-K rocks.
- Similar characteristics to other pore pressure related cases.



Pore Pressure

- More distant cases have similar characteristics.
- Plausible that stimulated fractures intersect pre-existing faults.
- More distant stages/wells still appear to be seismogenic in some cases.

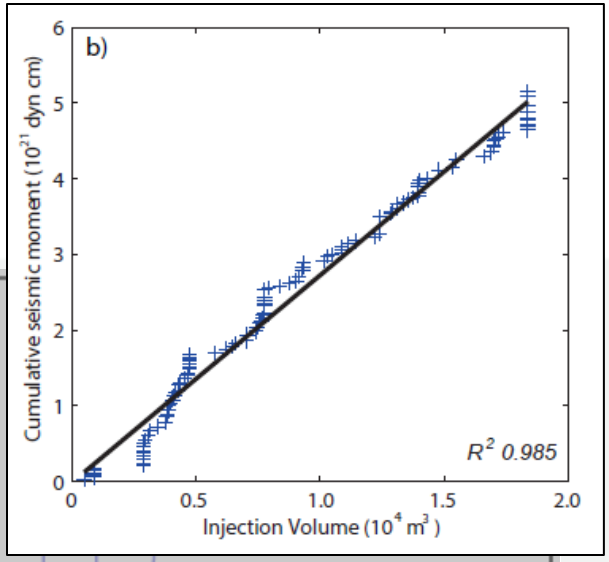


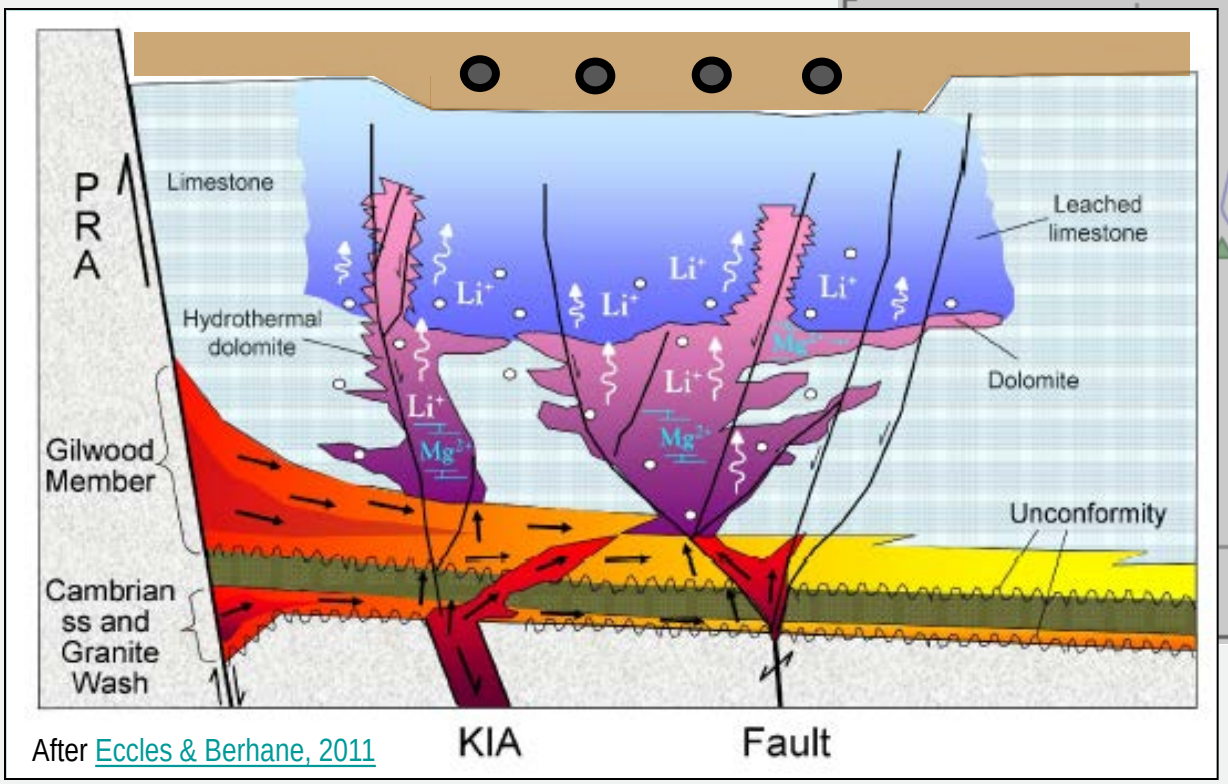
Pore Pressure

- Reef margin associated with EQs & HTD.

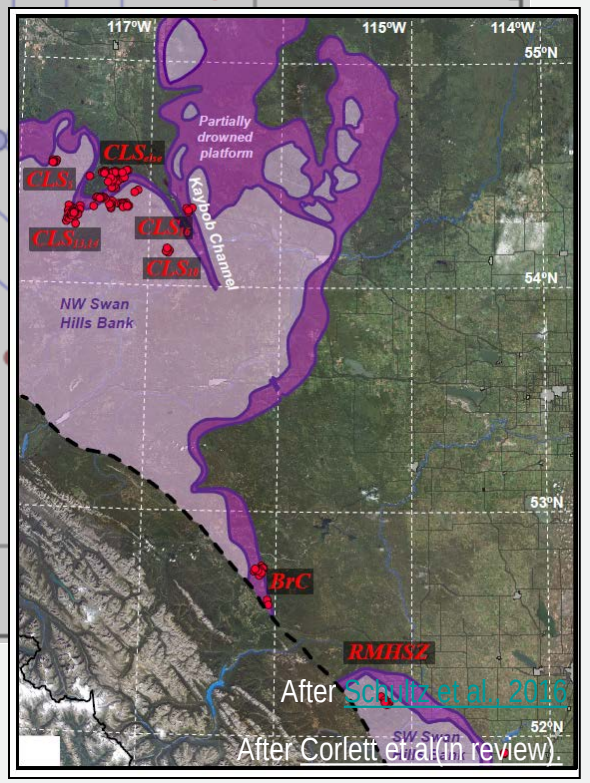
  Flower structures typical for HTD, allows

  for increased hydraulic communication.





After Eccles & Berhane, 2011

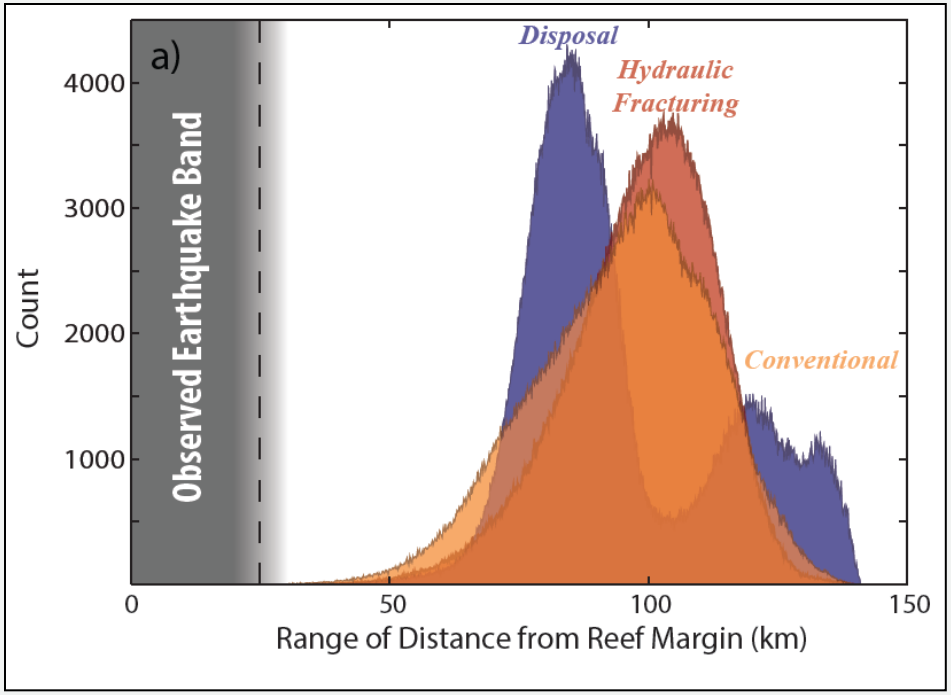


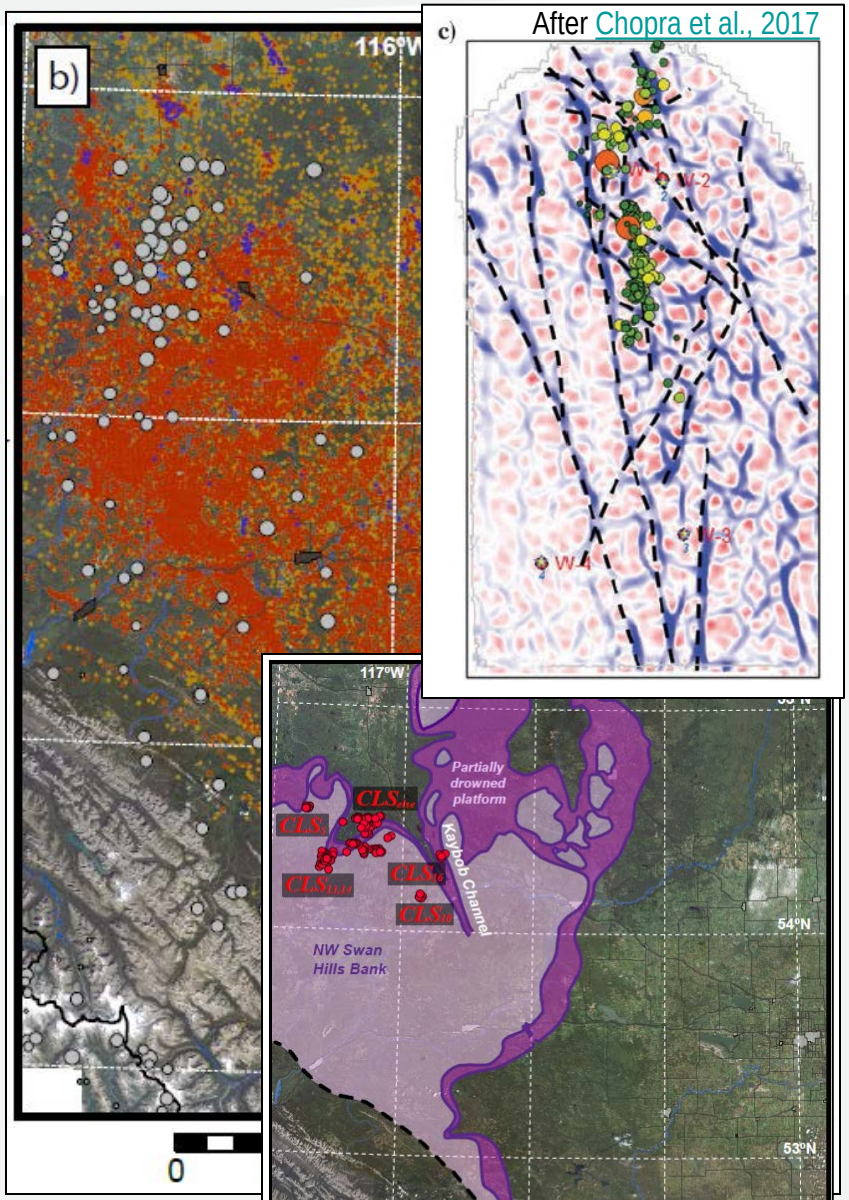
After Schultz et al., 2016

After Corlett et al. (in review).

Physical Rationale?

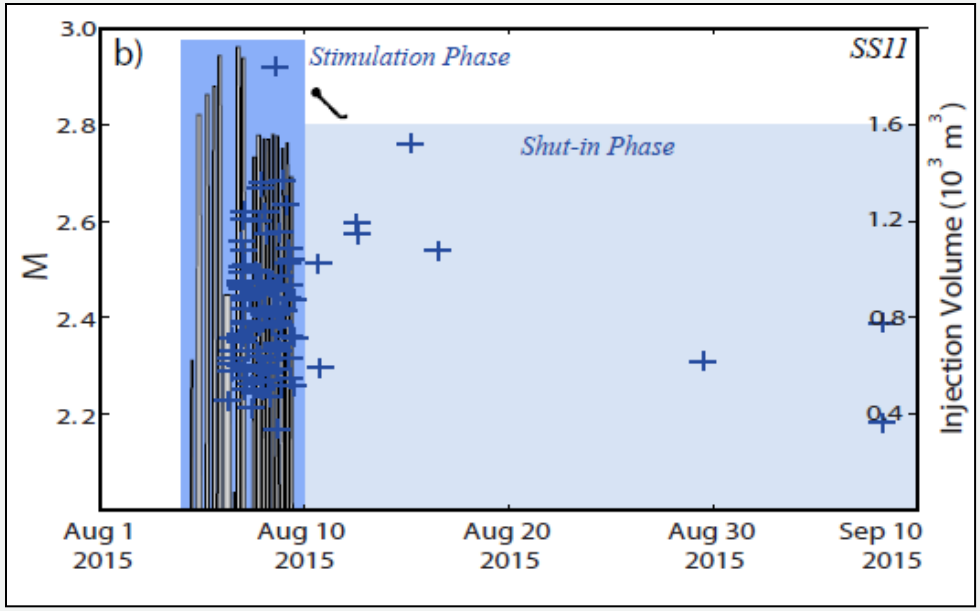
- **Statistical Swan Hills & Induced EQs association.**
- **Margin has been hydrothermally dolomitized.**
- **HTD requires extensional/transtensional tectonics.**
- **Some faulting evidence of highly faulted network.**

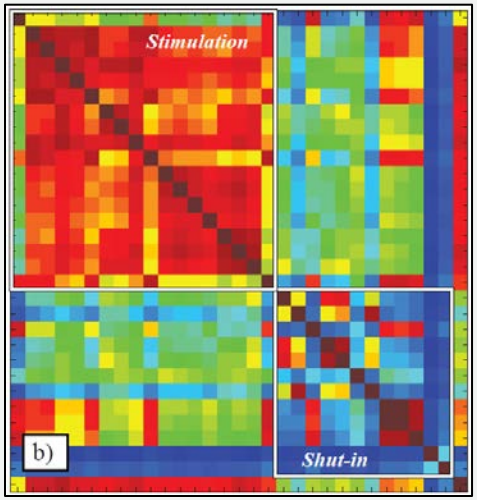




Second Order Poroelastic Effects

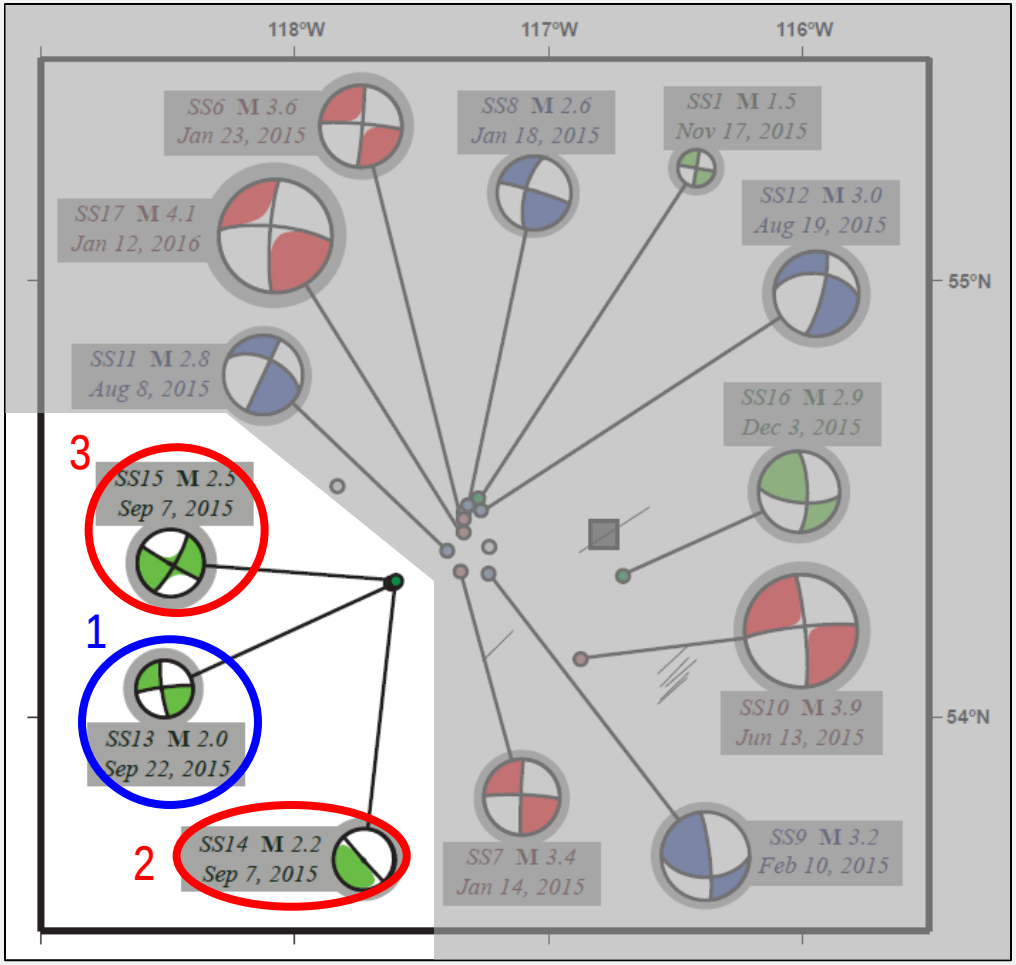
- Observation of seismicity back-front after shut-in, change in rate influenced by poroelastic effects.
- Many clusters observe largest earthquake after well shut-in, most notably the first TLP red-light case.



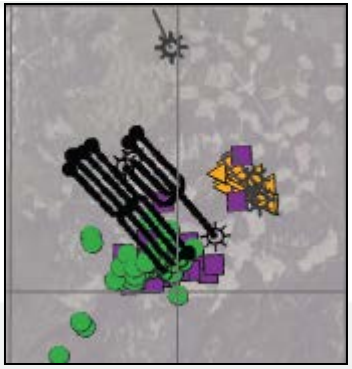


Case: *SS13-SS15*

- Clusters SS13-SS15 are all triggered by the same well, other cases observe one cluster per pad completion.
- SS13 occurs first and is followed by SS14 & SS15.
- However, only SS13 has optimal MT orientations for the stress field.

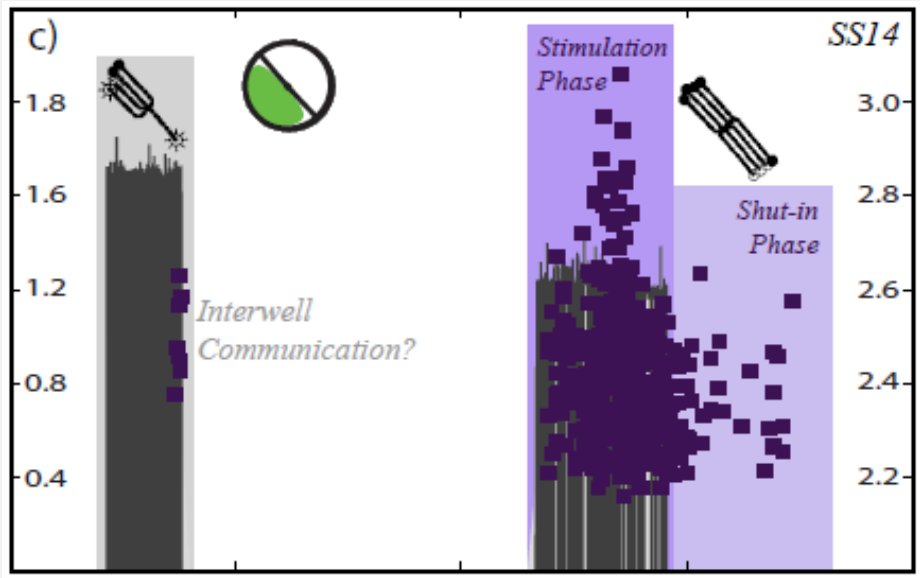


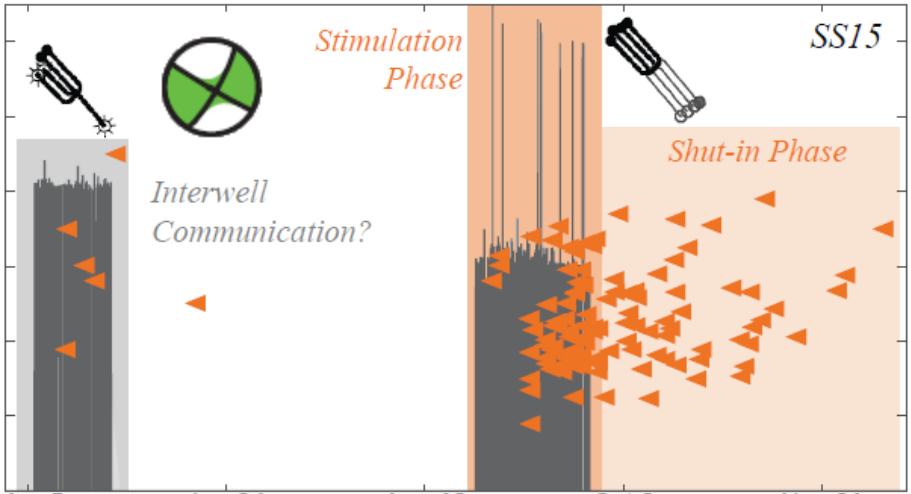
Case: *SS13-SS15*



- Clusters SS13-SS15 are all triggered by the same well, other cases observe one cluster per pad completion.
- SS13 occurs first and is followed by SS14 & SS15.
- Adjacent well completes prior to main seismogenic well, a few events observed during adjacent well stimulation. Could be priming area for events?

AGS





Summary

- **Duvernay related EQs are clustered in time & space and correlated to HF operations.**
- **MT results consistent with stress field (SS & ~50° Sh-max).**
- **MT & DD results suggest faults with N-S strike orientation, dipping subvertically from Duvernay to Precambrian.**
- **Overall, seismic observables are interpreted as dominantly pore pressure triggered, second order (poroelastic?) effects are observed throughout the clusters.**

Schultz, R., Wang, R., Gu, Y.J., Haug, K., Atkinson, G., (2017). A Seismological Overview of the Induced Earthquakes in the Duvernay Play near Fox Creek, Alberta, Journal of *Geophysical Research: Solid Earth*, 122, 492-505, doi: 10.1002/2016JB013570.

Questions

- **Send your questions or comments to:**

Ryan Schultz, Seismologist

Alberta Geological Survey

(780) 644 5530

Ryan.Schultz@aer.ca

Thank you