



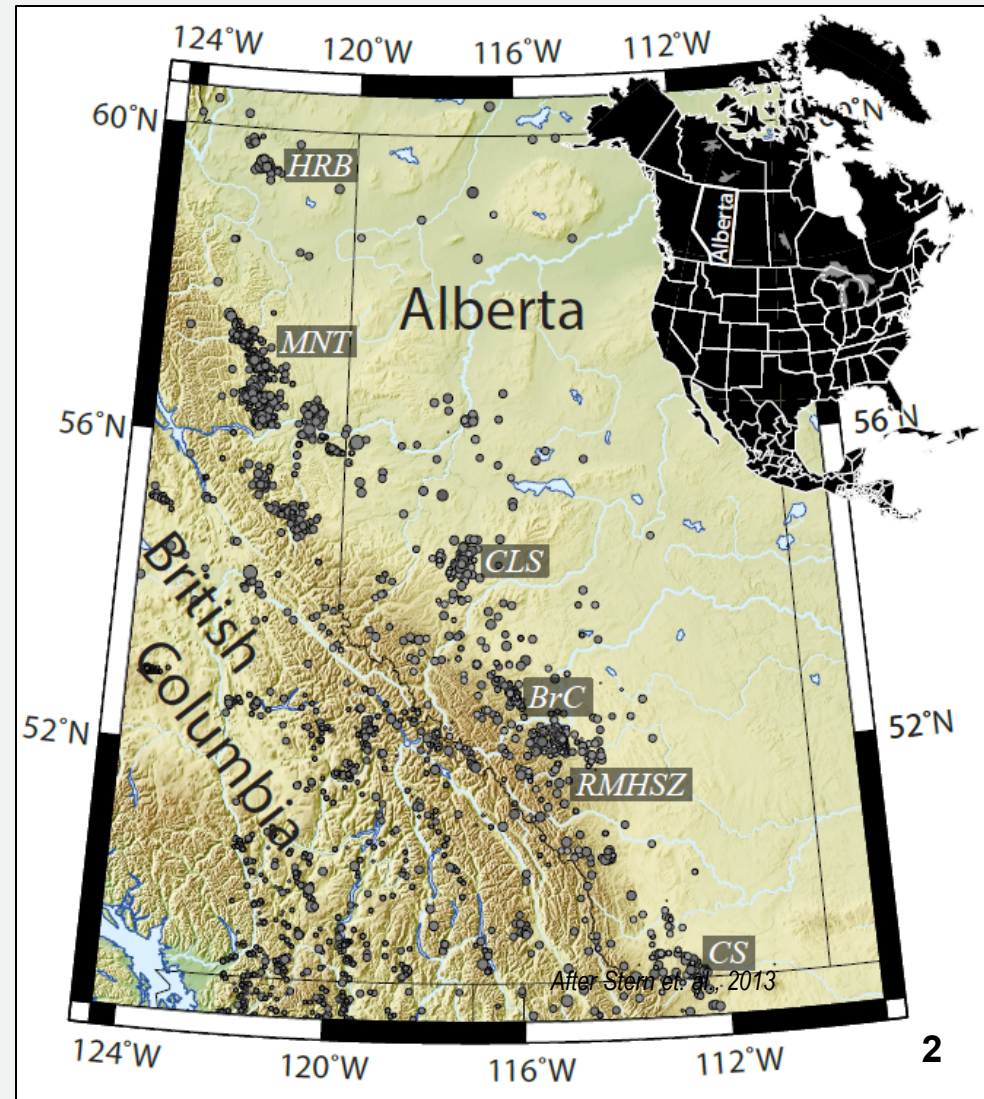
Overview of Seismic Monitoring and Earthquake Studies at the Alberta Geological Survey

Virginia Stern, Ryan Schultz, Javad Yusifbayov, and Todd Shipman



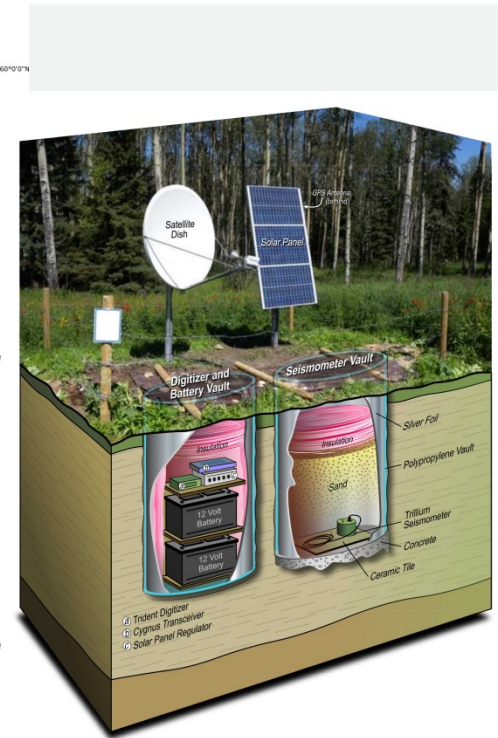
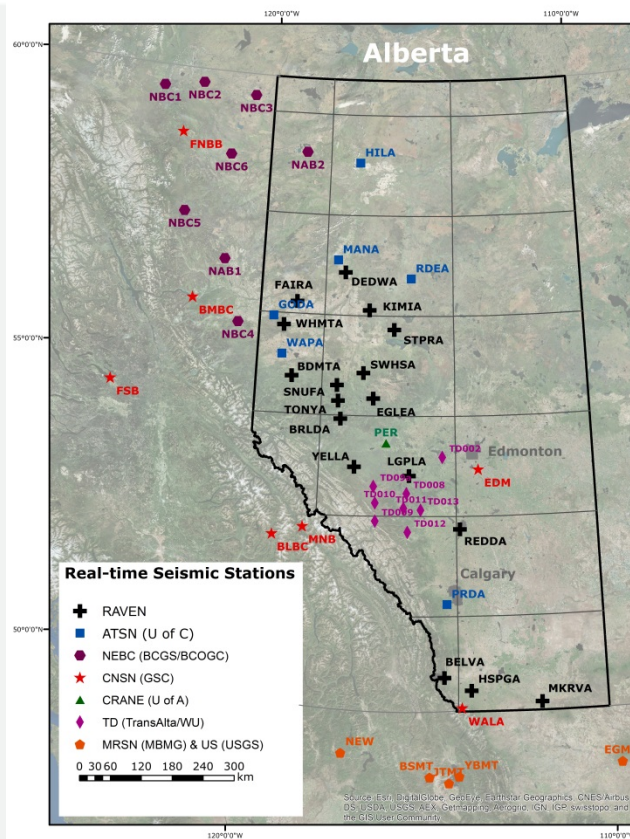
Seismicity in the WCSB

- 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.



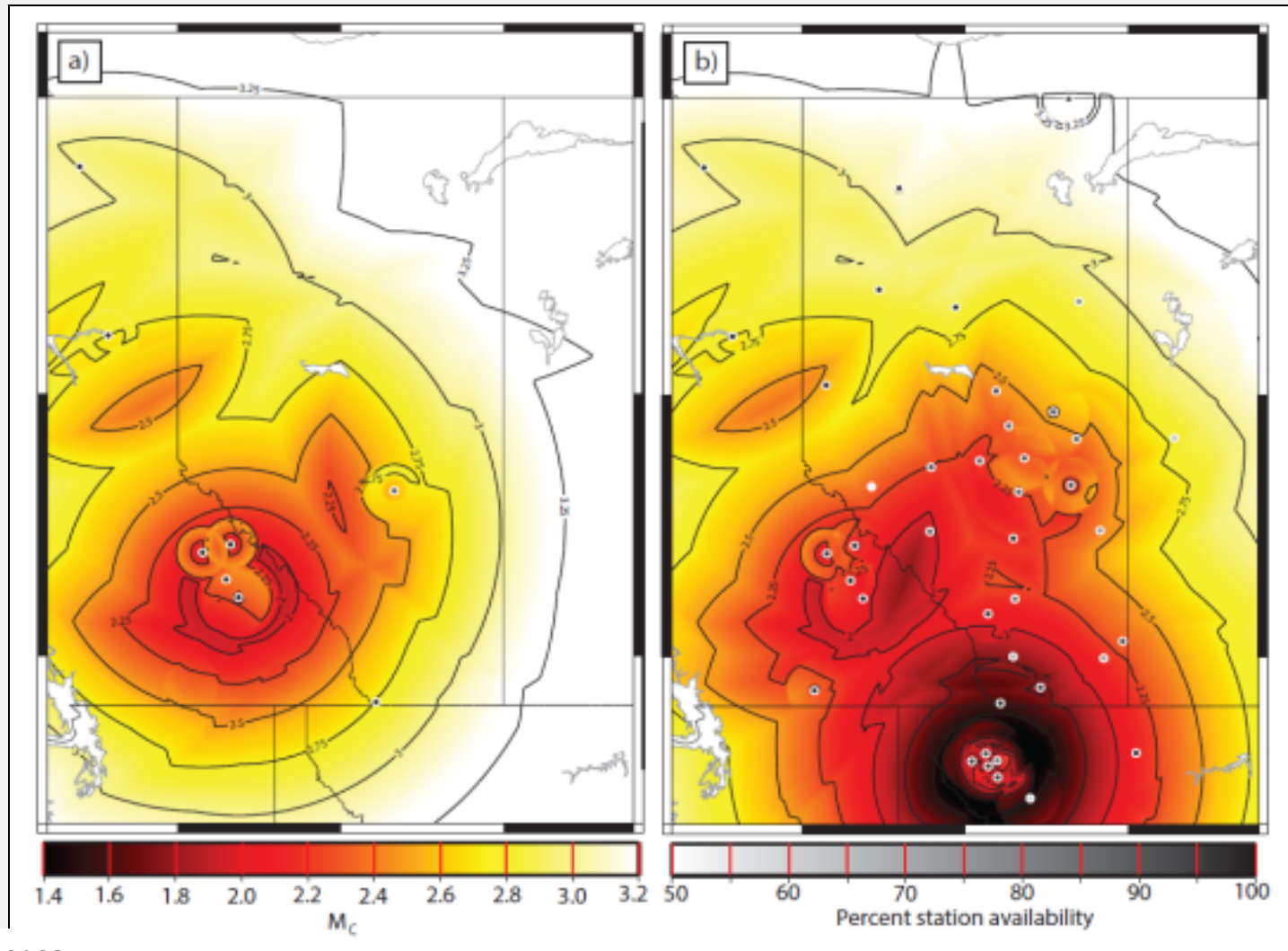
Seismic Monitoring in Alberta

Since 2010, the AER, through the Alberta Geological Survey (AGS), has been directly monitoring natural seismicity levels in Alberta and assessing subsurface energy resource operations (mainly completion activities such as hydraulic fracturing) for potential links to induced seismicity



Stern, V.H., Schultz, R.J., Shen, L., Gu, Y.J. and Eaton, D.W. (2013): Alberta earthquake catalogue, version 1.0: September 2006 through December 2010; Alberta Energy Regulator, AER/AGS [Open File Report 2013-15](#), 29 p.

Detection Performance



All Stations used in solutions of events

Real-time:

CNSN (PGC), ATSN (U of C),
NBC (BCOGC), MRSN
(MBMG), US-REF (USGS),
RAVEN (AGS/AER)

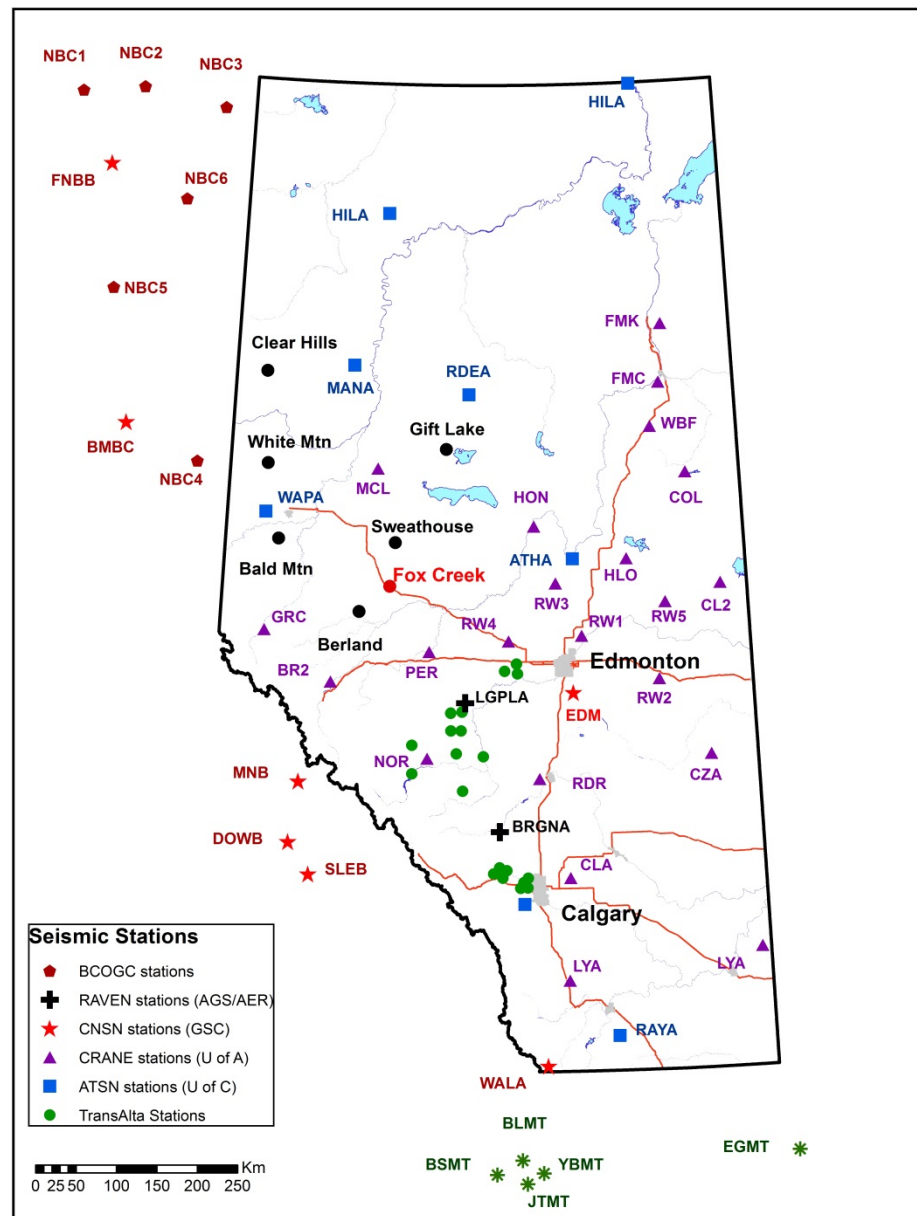
Campaign mode:

CRANE (U of A), RAVEN
(AGS/AER)

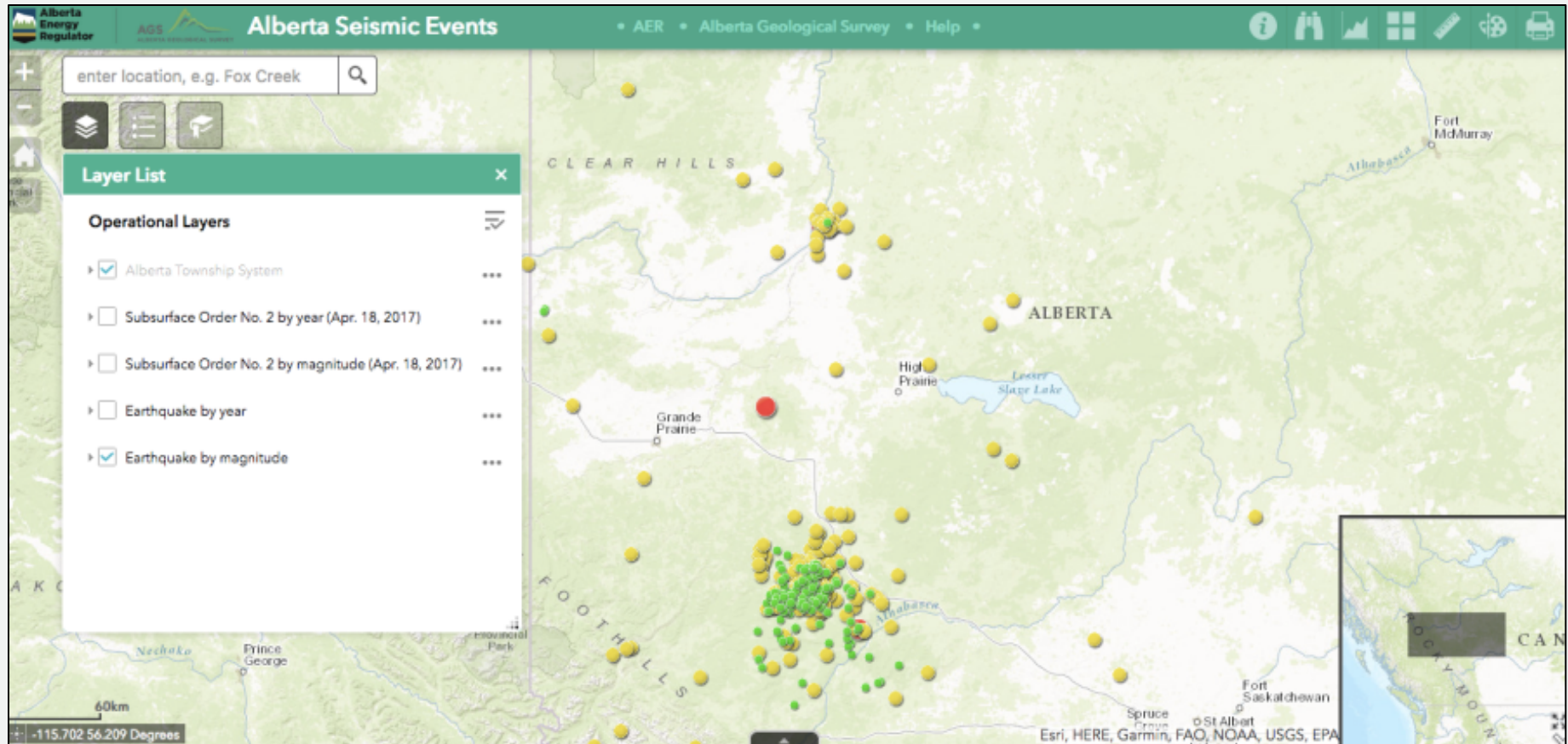
Future RAVEN stations (Black circles):

Red Deer

Fox Creek



Interactive Earthquake Map



<http://ags-aer.maps.arcgis.com/apps/webappviewer/>

E-Mail Alert System

- Multiple individuals receive notification of an earthquake
- Occurs ~5 min post event

Event ID: 639797

latitude: 52.9792 longitude: -117.2145 depth: 2 time : 5/21/2017 21:08:03.374 magnitude: 2.180000

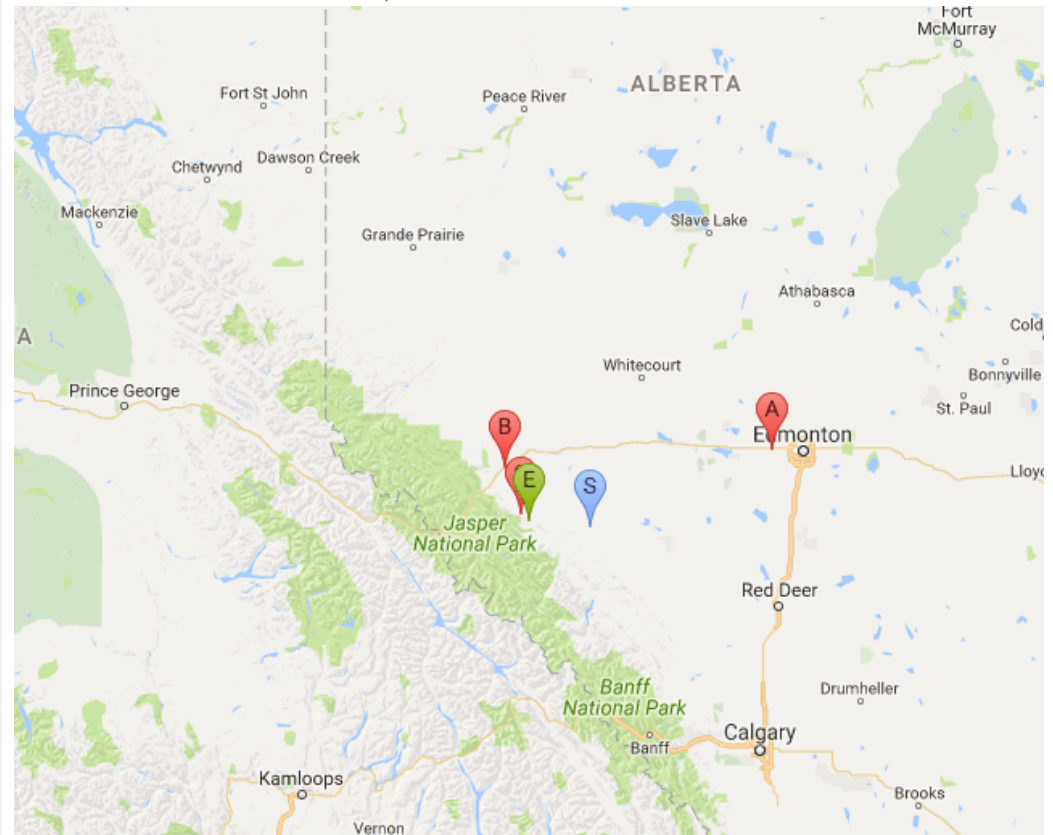
Nearest City: Spruce Grove Distance: 229.777756 km

Nearest Town: Hinton Distance: 53.013627 km

Nearest Small Settlement: Cadomin Distance: 9.316578 km

Marker E indicates the estimated earthquake location. A B C are respectively City, Town and Small Settlement

Nearest Station: Marker S - TD09A, Distance from event location : 55.762922 km



Traffic Light Protocol

- AER enacted TLP through Subsurface Order #2 Feb 19th 2015.
- Duvernay operations must conduct seismic monitoring to detect M_L 2.0 event within 5 km of any affected well.
- Events $\geq 2.0 M_L$ must be reported, events ≥ 4.0 must suspend operations, & submit data to regulator.
- Operations can only resume after AER approval.
- 2 TLP red-light cases to date.



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AER Traffic Light System - Duvernay Zone, Fox Creek



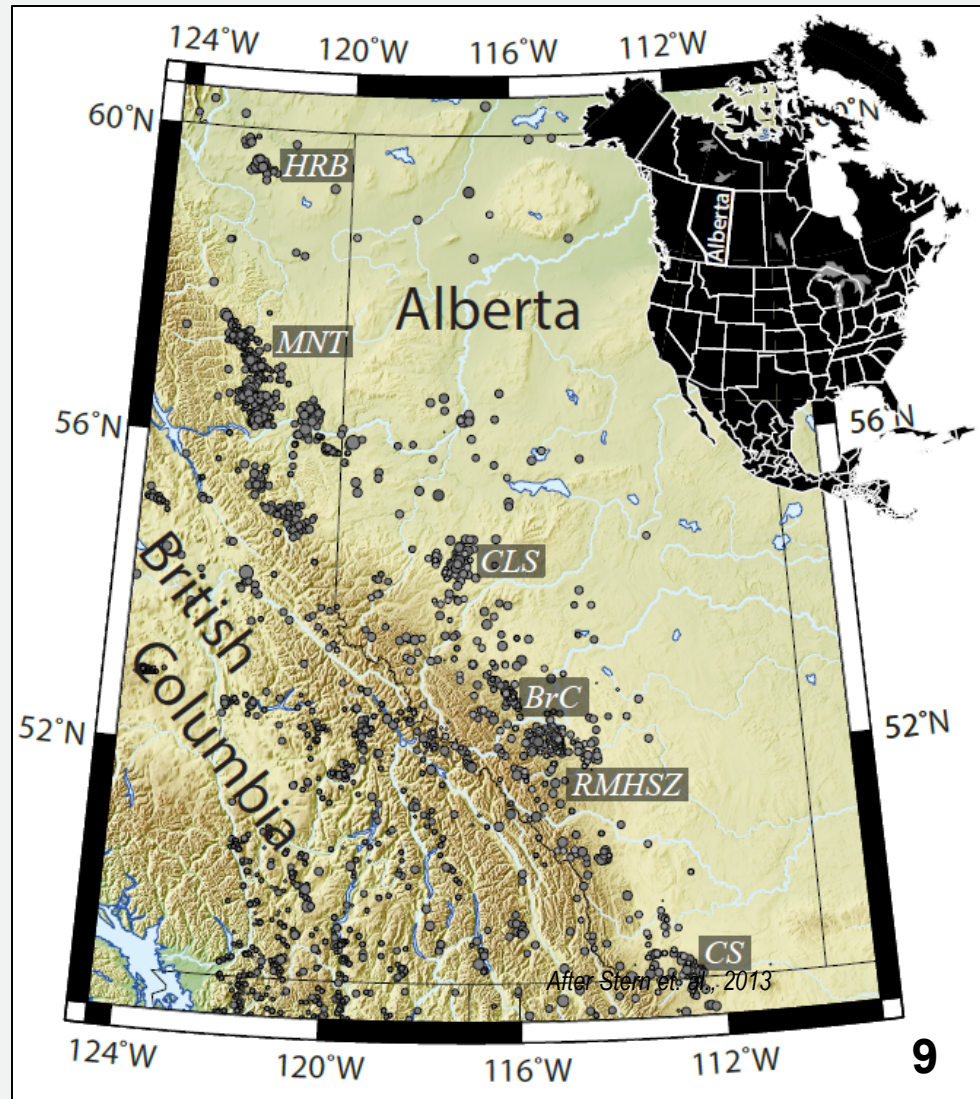
- $\geq 4.0 M_L$
cease operations,
inform the AER
- $\geq 2.0 M_L$
inform the AER,
invoke response plan
- $< 2.0 M_L$
no action required

March 2016

Alberta Energy Regulator

Seismicity in the WCSB

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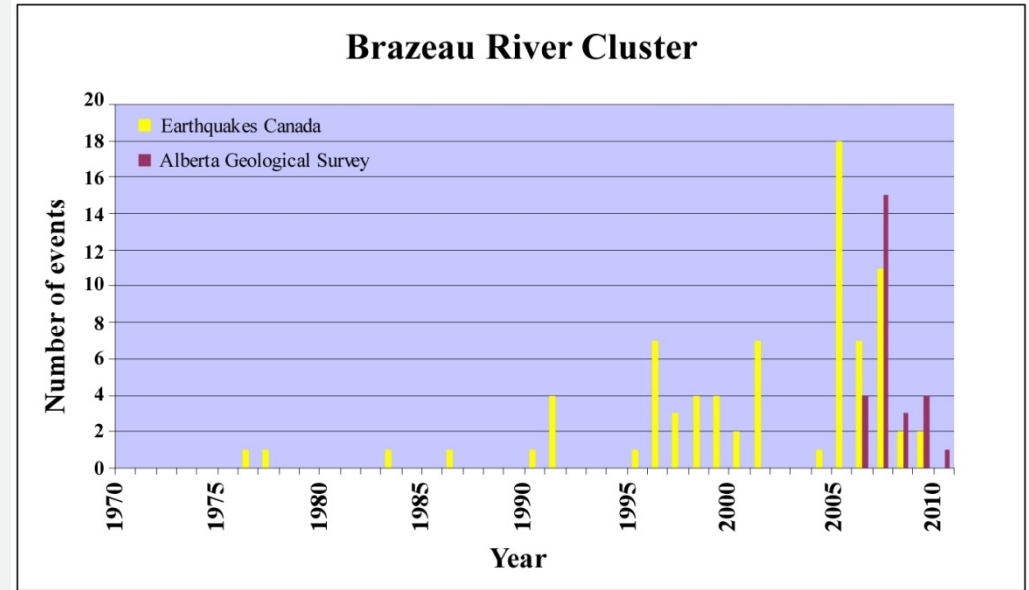
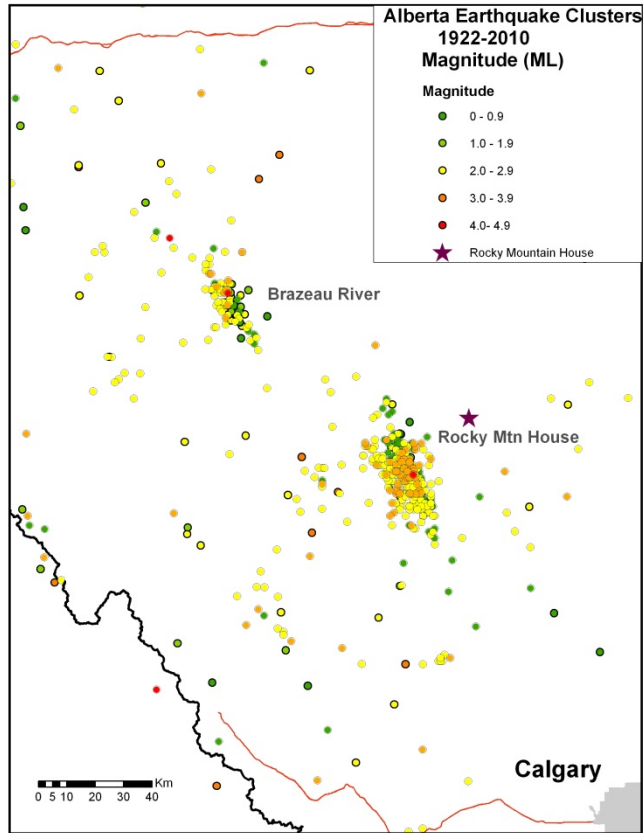


An investigation of seismicity clustered near the Cordell Field, west-central Alberta and its relation to a nearby disposal well

Ryan Schultz, Virginia Stern, Yu Jeffrey Gu



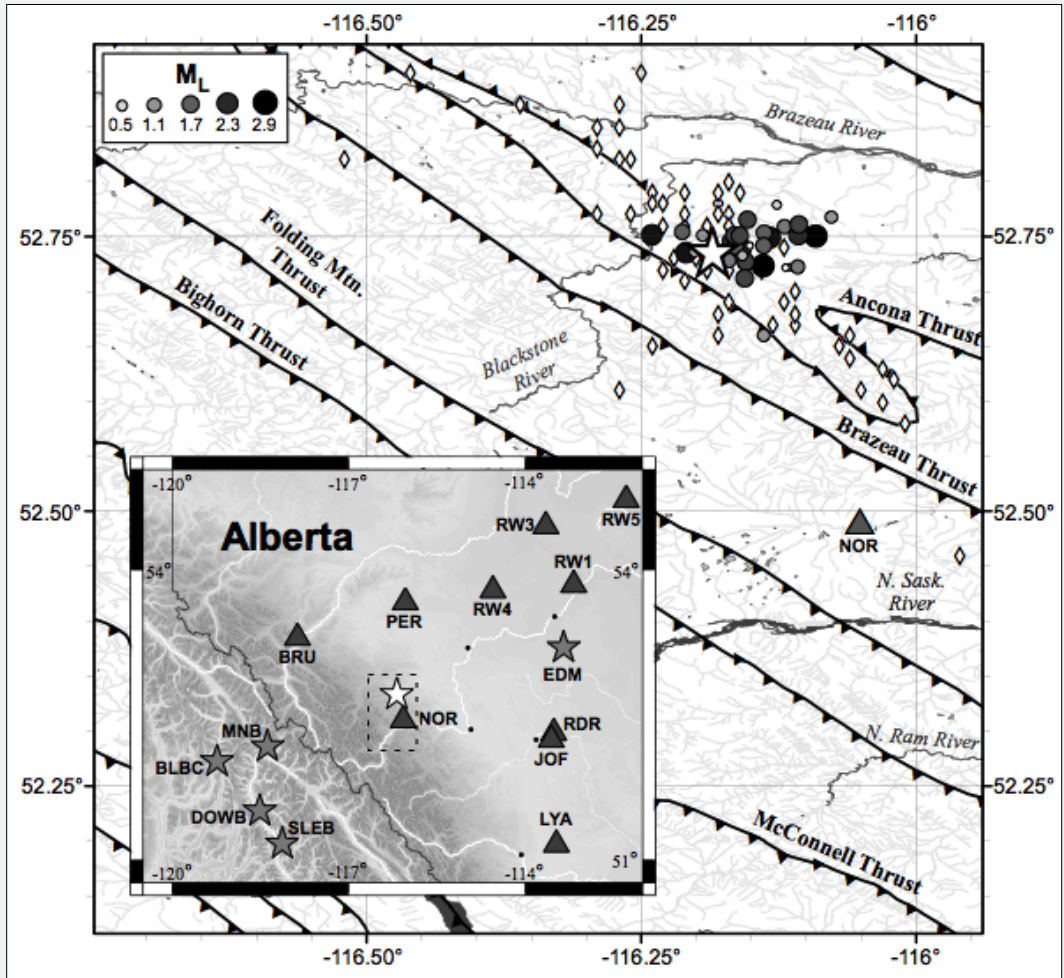
Brazeau River Events



Stern et al. (2013): Alberta Earthquake Catalogue, Version 1.0: September 2006 through December 2010, AER/AGS Open File report, 2013-15.

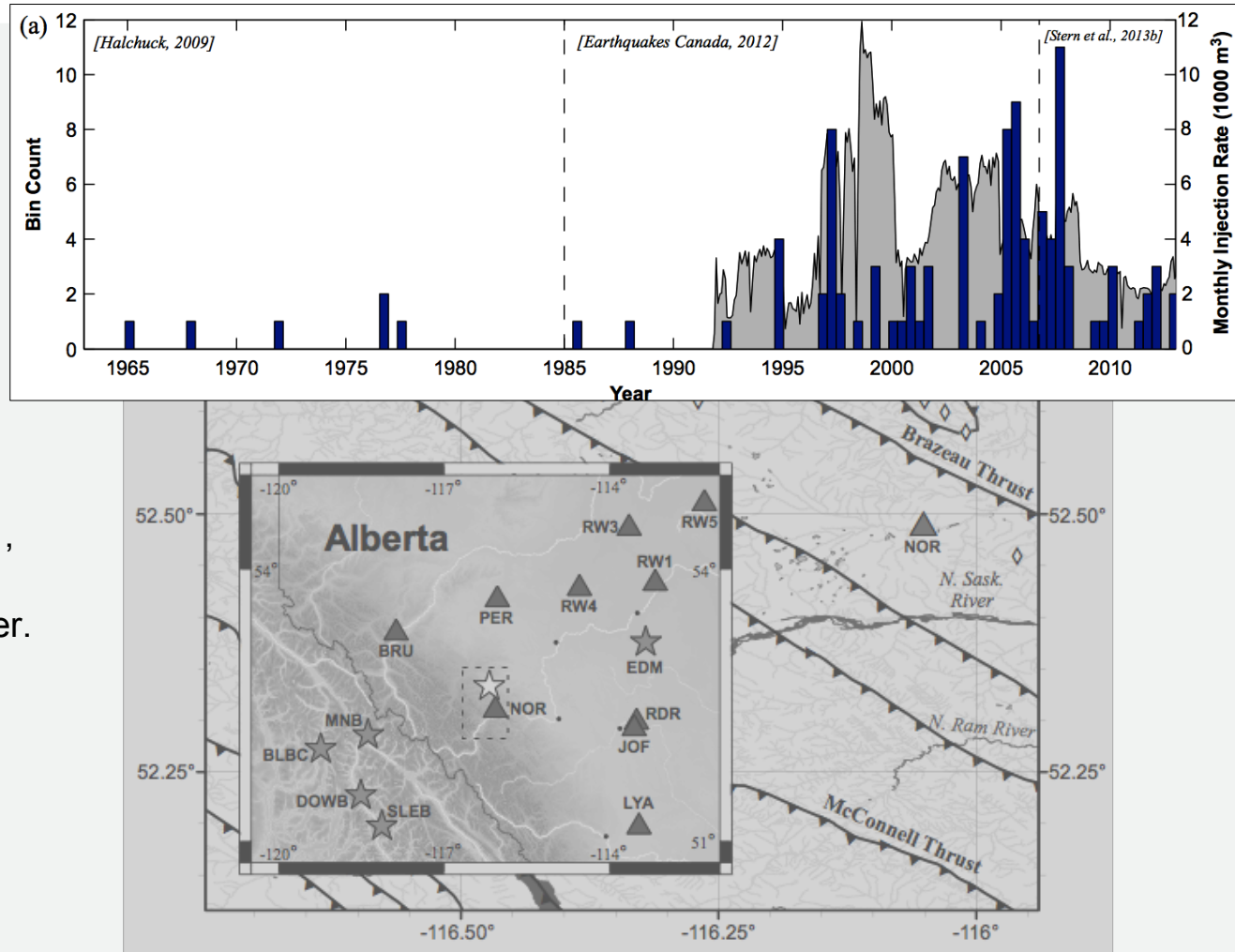
Disposal Activities & Seismicity

- Catalogued data surrounds a waste water disposal well.



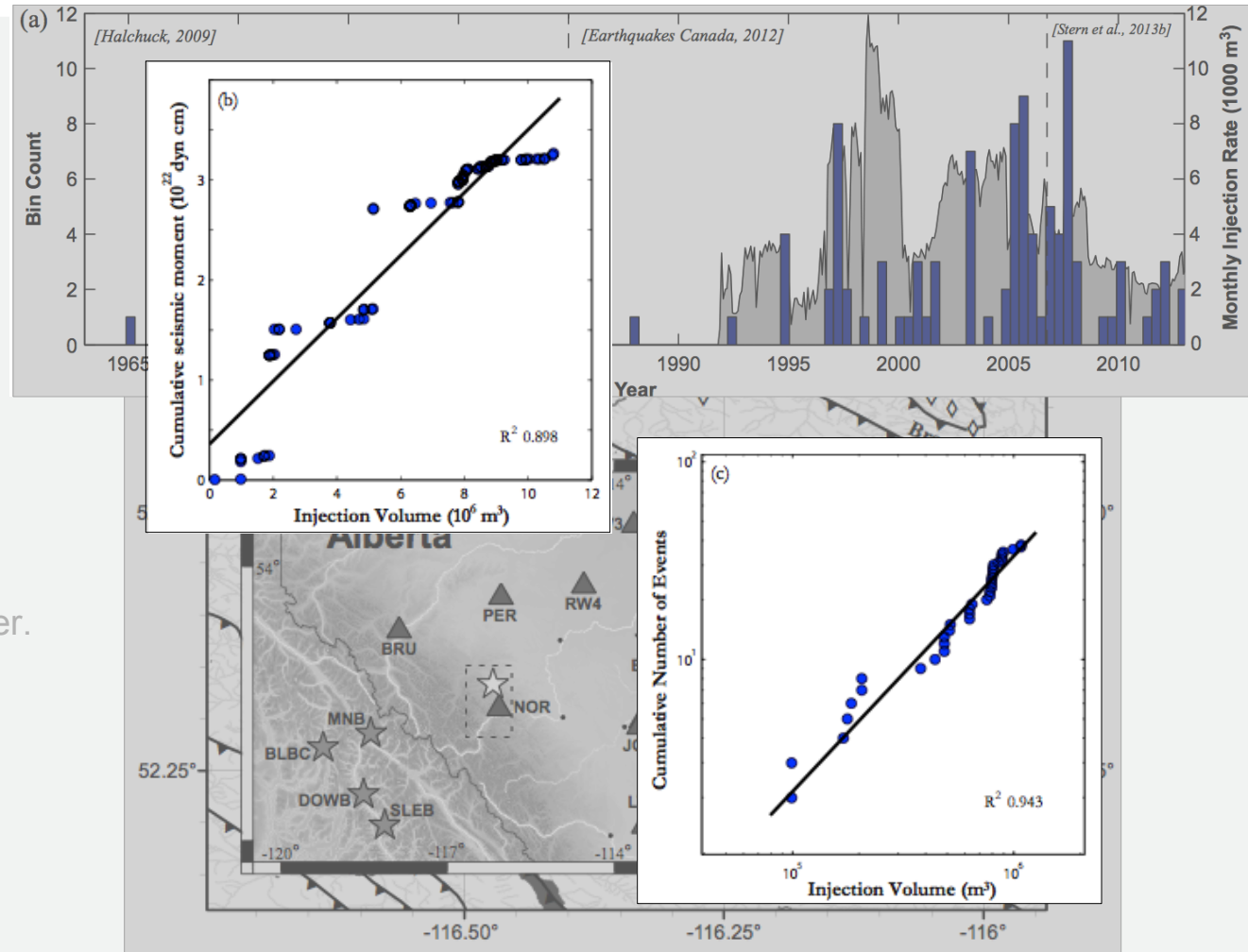
Disposal Activities & Seismicity

- Catalogued data surrounds a waste water disposal well.
- Seismicity onset is skewed in time.
- Injection started October 1991, disposed of 10^6 m³ waste water.
- Are these related?



Disposal Activities & Seismicity

- Catalogued data surrounds a waste water disposal well.
- Seismicity onset is skewed in time.
- Injection starts October 1991, disposed of 10^6 m^3 waste water.
- Are these related?
- Good correlations!



Summary

- **Statistically significant temporal correlation.**
- **Similar waveform character of recorded events.**
- **Spatial proximity to Cordel disposal well.**
- **Evidence for lineation of events.**
- **Consistency with other cases of injection induced seismicity.**



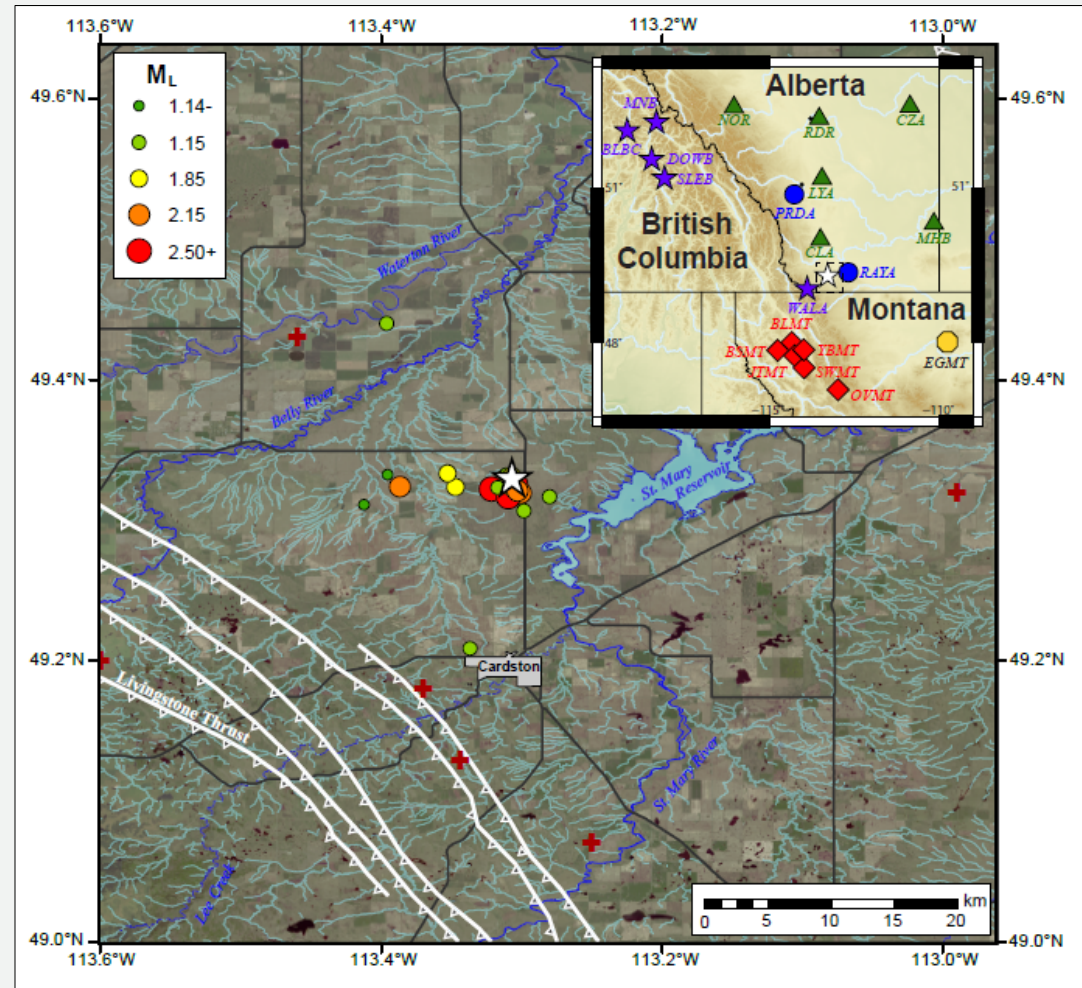
Hydraulic fracturing of the “Alberta Bakken” and the Cardston Earthquake Swarm

Ryan Schultz, Shilong Mei, Dinu Pana, Virginia Stern, Yu Gu, David Eaton



The Cardston swarm

- Cluster of events in southern Alberta
~13 km north of Cardston
- More than 25 located events
- Events approaching M_L 3.0
- Events occur in the vicinity of a horizontal well completed in the Exshaw Formation.

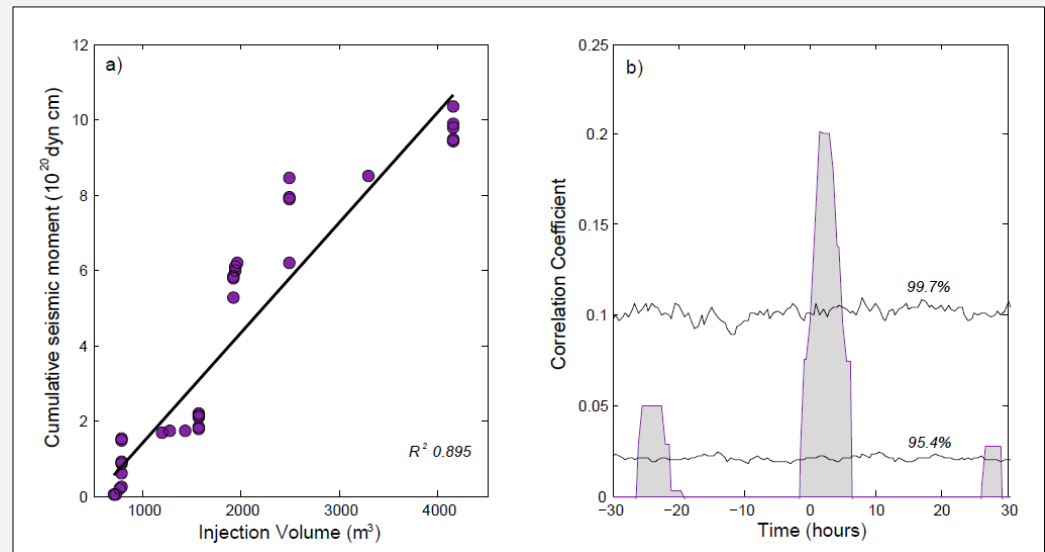
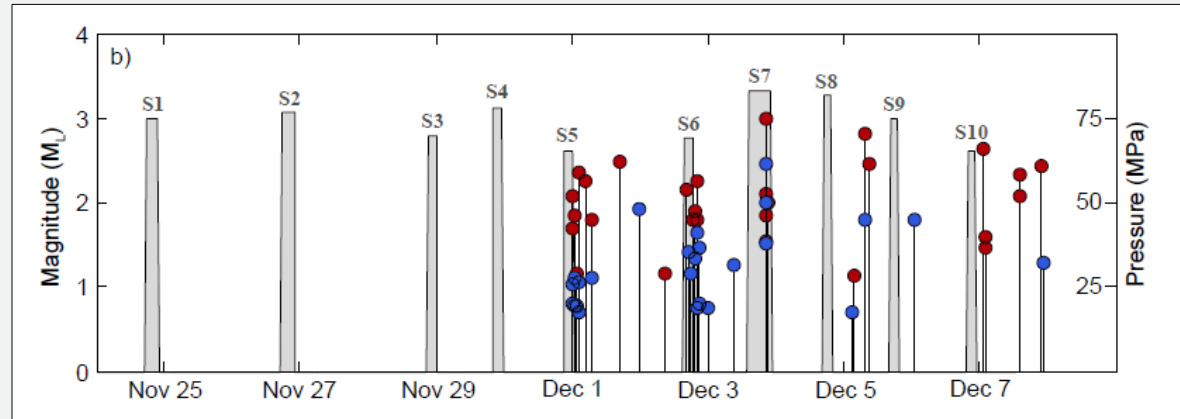


The Cardston Swarm

- Newly recognized swarm of events starting Dec 1st 2011.
- Events start after fifth treatment stage, w/ ~1.5 hour lag time.

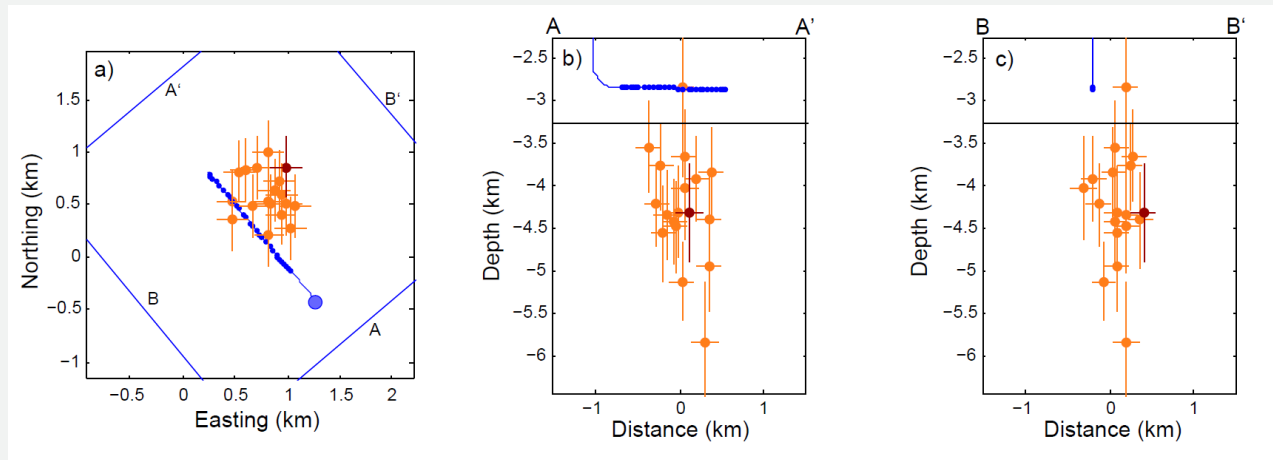
Similar to other published case studies.

- Timing of events highly correlated with timing of individual fracking stages to >99.7% confidence.



Double-Difference Hypocentres

- Morphology of events?
- Use double difference location algorithm to determine event geometry.
- Cluster centred ~200 m from well laterally.
- Events are primarily located within the Archean basement.
- Any structure observed is simply due to the statistics of error.



Summary

- **Statistically significant temporal correlation and proximity to well**
- **Events occur primarily during frack stages, after the fifth.**
- **Events induced by increased pore pressure within fault, communicated into the basement via a Late Cretaceous extensional fault**
- **Consistency with other cases of hydraulic fracturing induced seismicity**
- **Reactivation of previously existing basement fault as normal/strike-slip?**



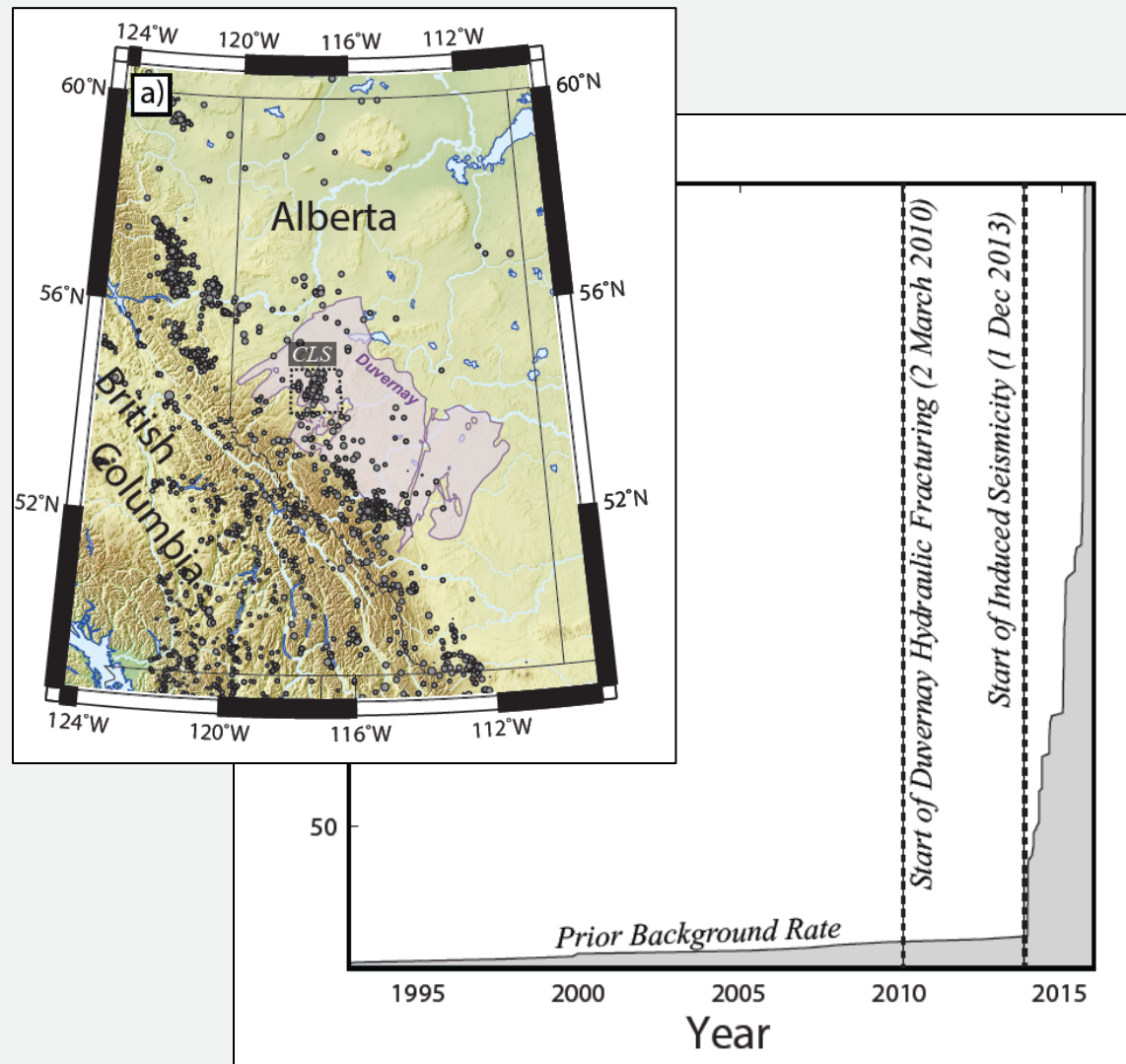
A Seismological Overview of the Induced Earthquakes in the Duvernay Play near Fox Creek, Alberta

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



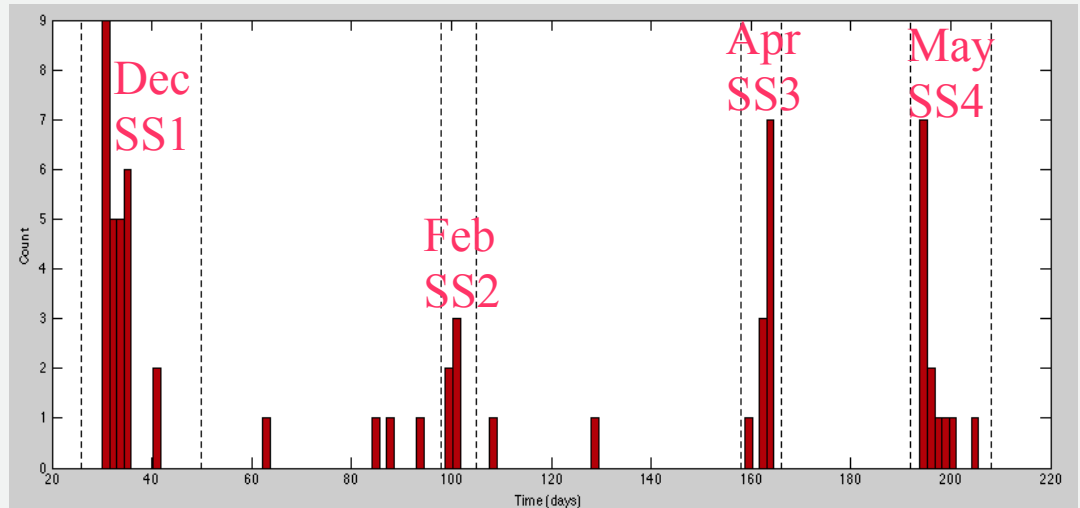
The Earthquakes Near Fox Creek

- 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.



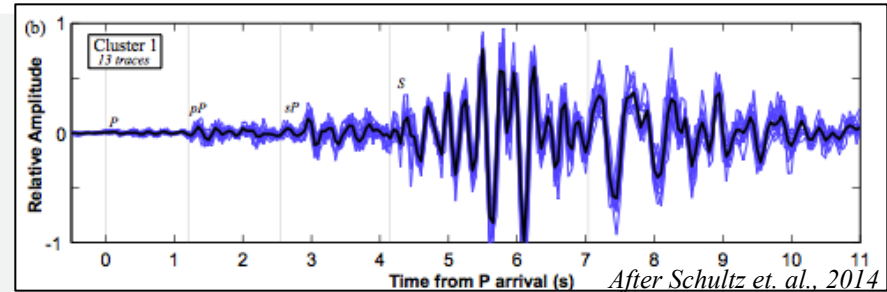
The Crooked Lake sequence

- New sequence of events starting Dec 1st 2013.
- Timing of events suggests four possible subsequences?
- Clustered in time during Dec, Feb, April, & May.

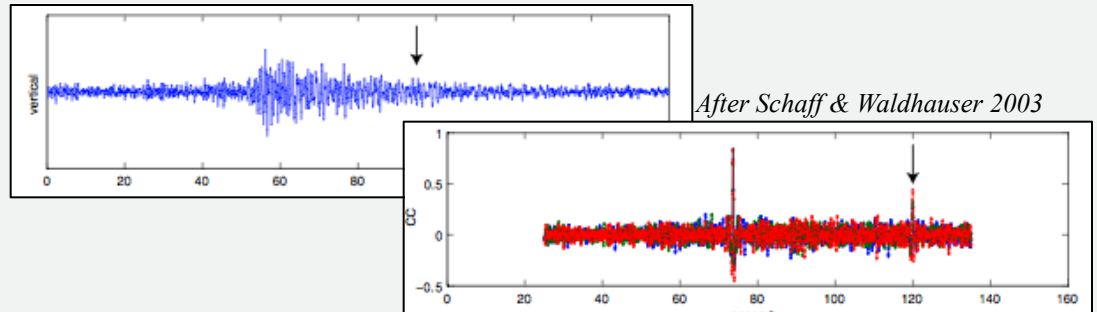


Methodologies

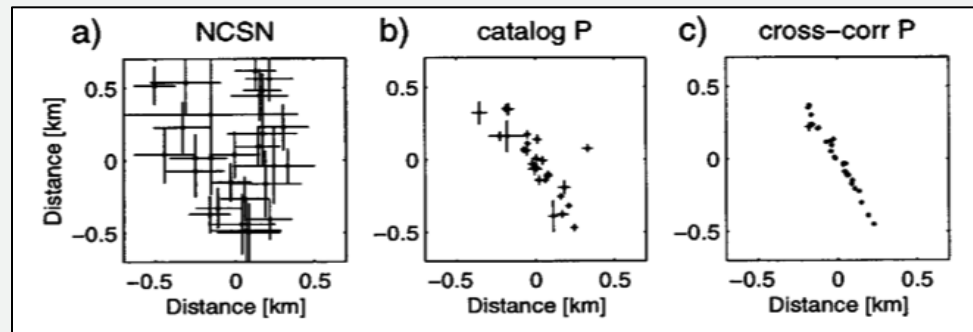
- Waveform multiplicity & correlation, examine event similarity.



- Cross correlation detectors to extend temporal catalogue.



- Double difference relocation to better constrain epicentres.



After Waldhauser & Ellsworth 2000

Summary

- ❑ **Crooked Lake sequence is composed of subsequences.**
- ❑ **Overall sequence is generally similar, although subsequences have distinguishable waveforms.**
- ❑ **Possible seismic waveform observation of shut-in for SS1?**
- ❑ **Spatial distribution of events follow trends according to timing of subsequence.**



Bridging Gaps in Induced Seismicity Hazard Forecasting in Alberta, Canada

Ryan Schultz

Hydraulic Fracturing Completion Volume is Associated with Induced Earthquake Productivity in the Duvernay Play

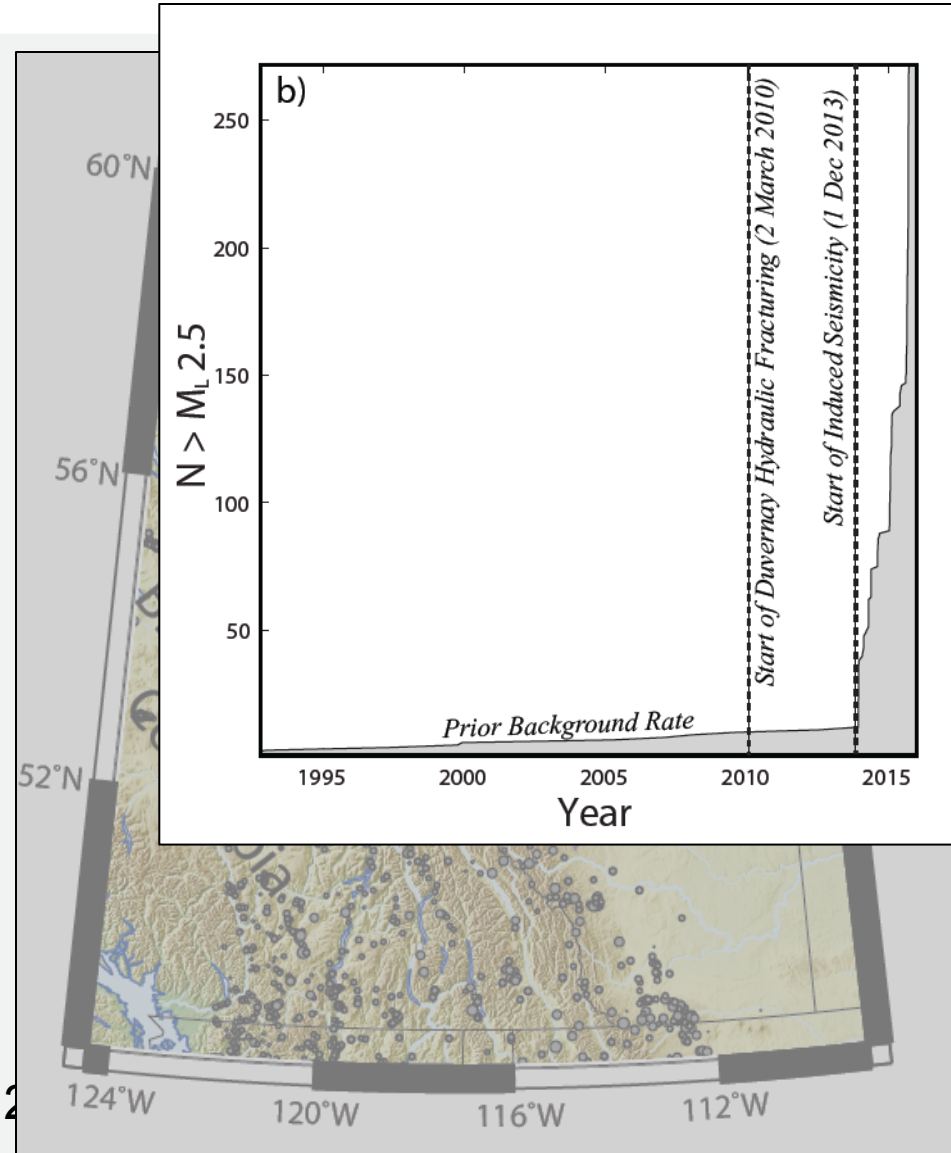
Ryan Schultz, Gail Atkinson, David Eaton, Yu Jeffrey Gu, Honn Kao



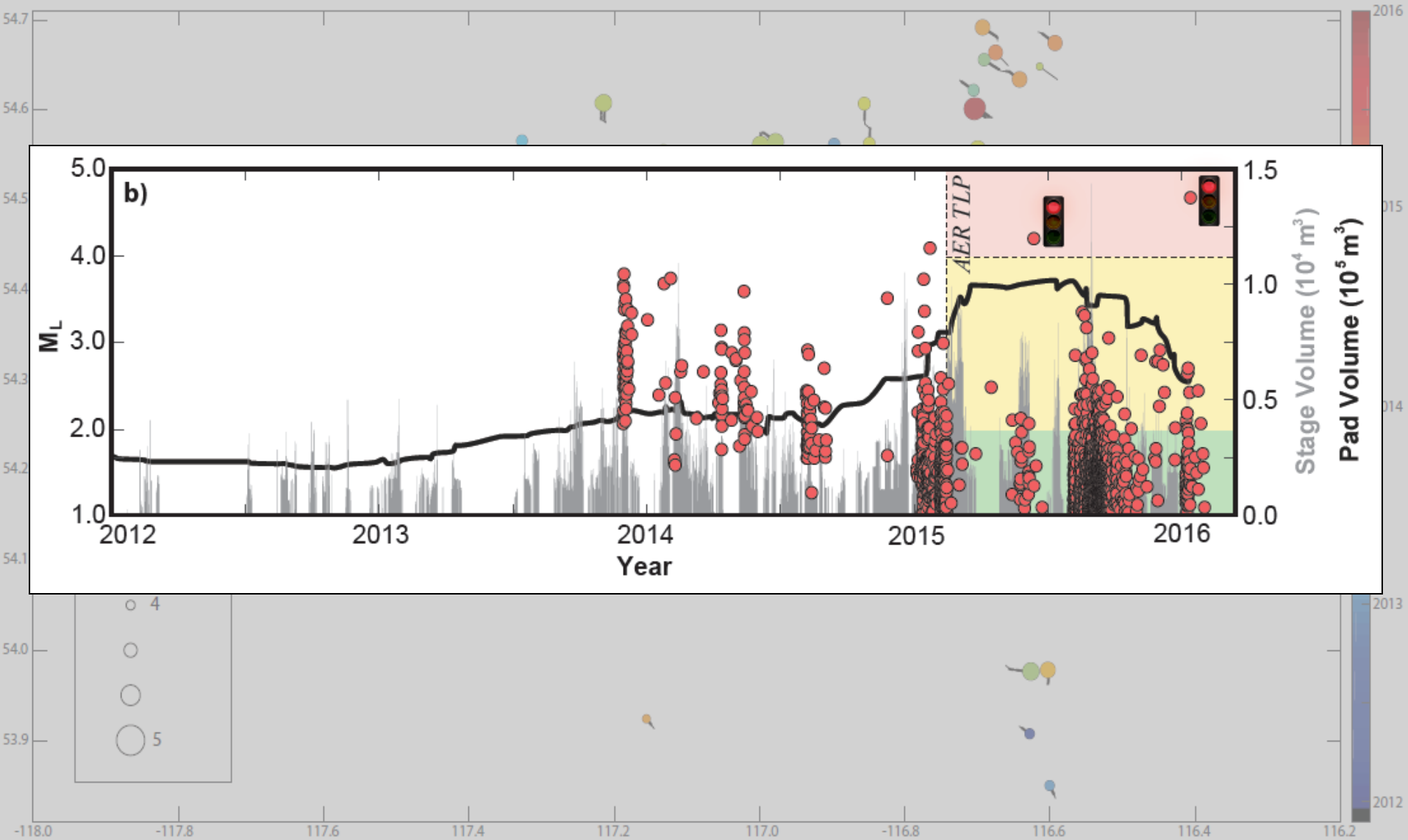
Seismicity in the WCSB

- 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.
- CLS is known to be related to HF of the Duvernay Formation [[Schultz et al., 2017](#)].
- Reason for ~3 year delay from first Duvernay HF and first EQs?
- Related to completion programs?

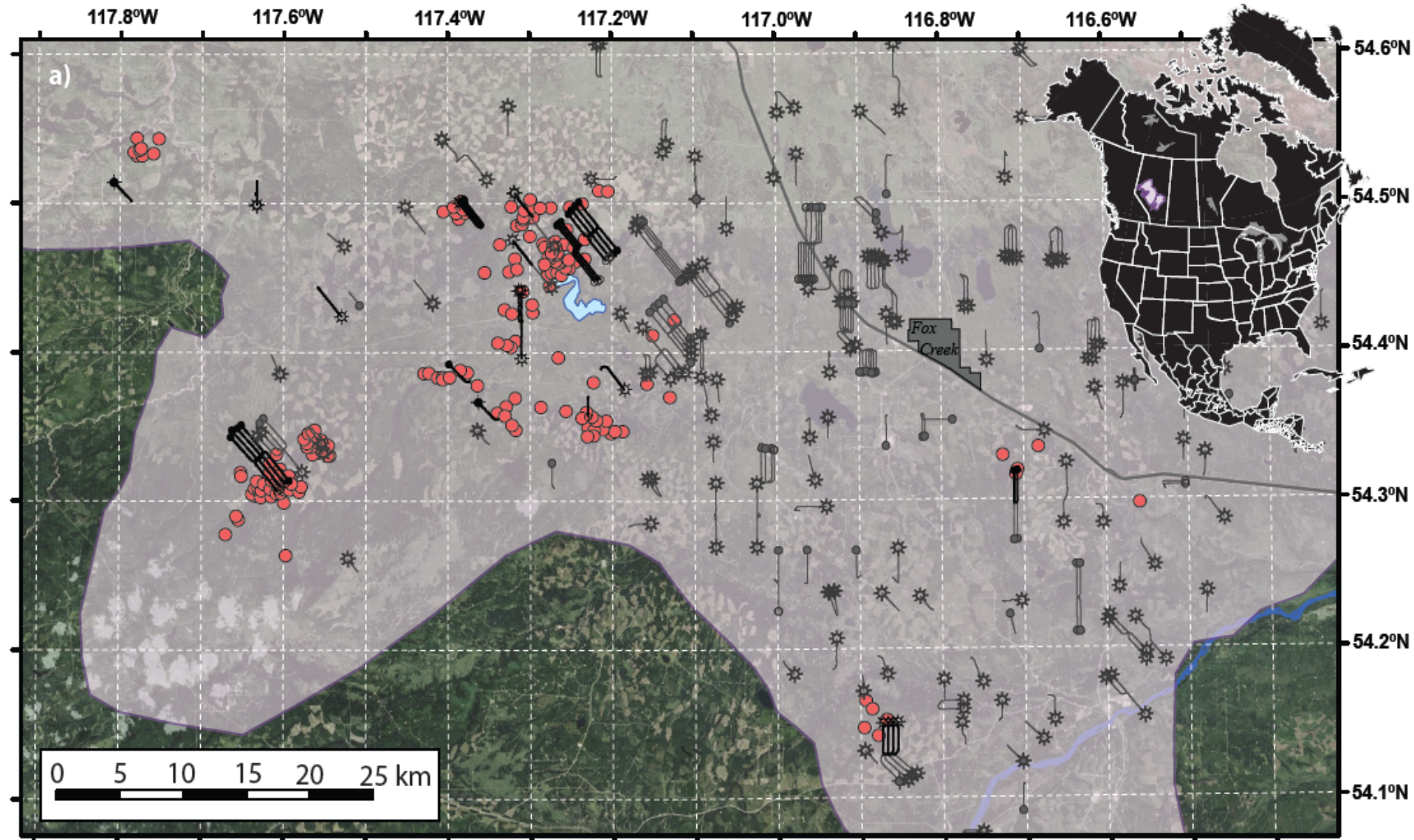
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HF Operations near Fox Creek



Spatiotemporal Association Filter



AER Tour Report Database

- **Good News:**
 - Operational records exist!
 - Includes stage averaged pressures, volumes, rates, proppants weights
 - **Bad News:**
 - Not in digital format, lots of manual data entry work (400+ pages per well).
 - Records could be more comprehensive and include pumping curves.
- www.ags.aer.ca

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The image displays a 'Well Drilling Completion Data Submission Cover Sheet' from the Energy Resources Conservation Board. The form includes the following information:

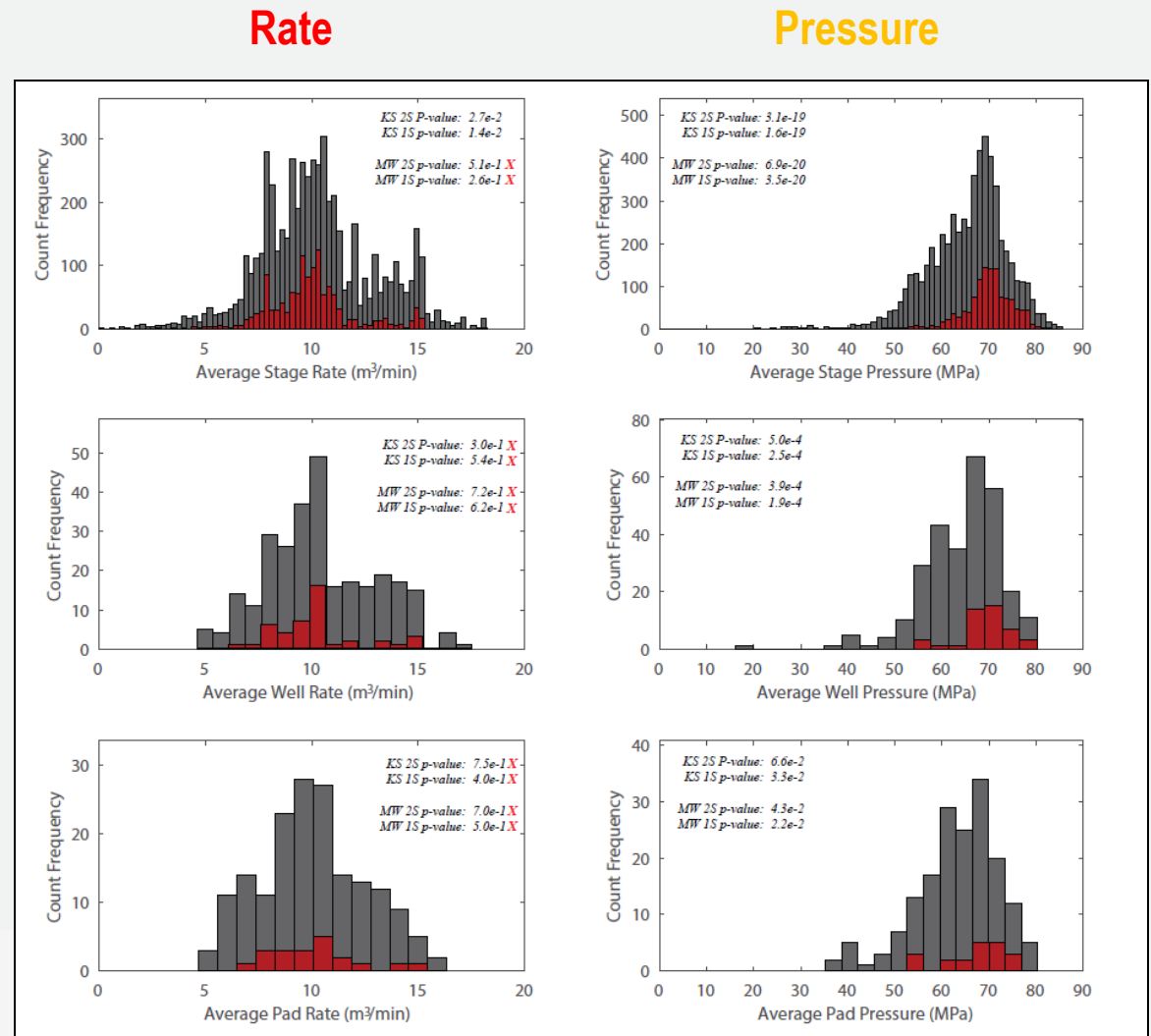
- Submission ID:** 1283513
- Submission Date:** Tuesday, January 10, 2012
- Licence Number:** 0434386
- JWIs:** 00/P9-P9-U04-25W4/3 Completion ✓
- Signature:** N. Marshall (with initials CF)
- Name:** Guy Marshall
- Date:** Jan. 10/12
- Address for submission:** Energy Resources Conservation Board, Core Research Centre, 3545 Research Way NW, Calgary, Alberta T2L 1Y7, Attn: Drill Cutting Library

The form also contains a section for 'TOUR 1' and 'TOUR 2' with detailed data entries. The bottom of the form shows a 'Page 8/9' and 'Page 2/2' indicator, along with a 'Report Printed: 1/10/2012' timestamp.

Statistical Tests:

Kolmogorov-Smirnov & Mann-Whitney U test

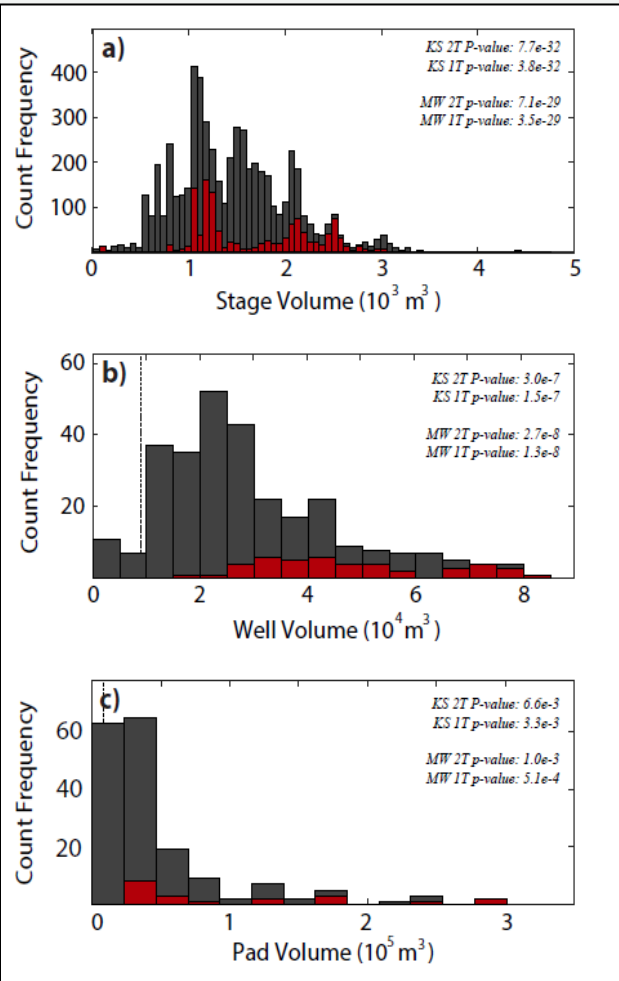
- Use Spatiotemporal association filter to distinguish seismogenic & aseismic pads.
- Do seismogenic pads (**red**) differ operationally from aseismic pads (**grey**)?
- Perform KS & MW tests to determine statistical difference.
- Tests repeated on a per stage, well, & pad basis.



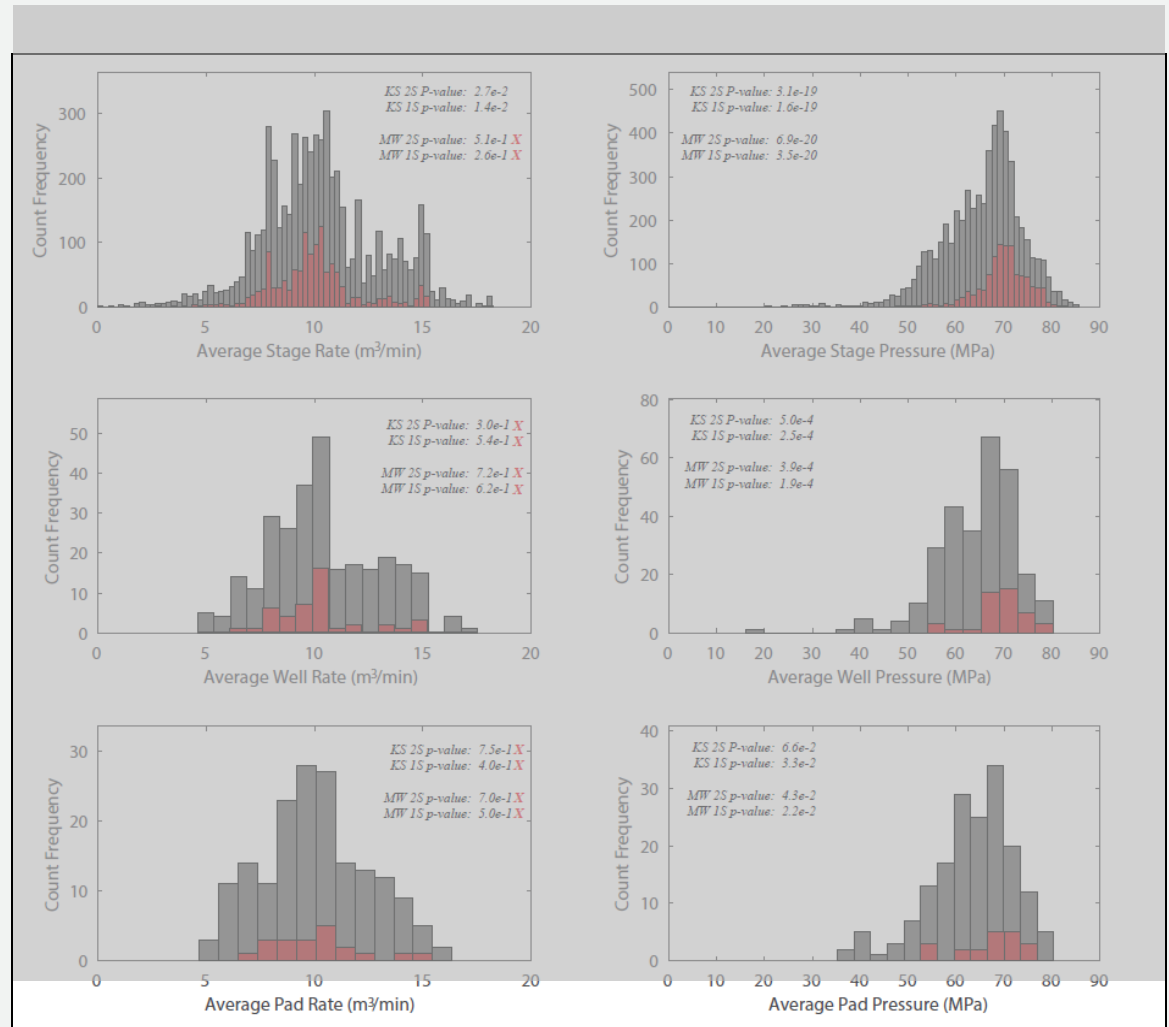
Statistical Tests:

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Volume

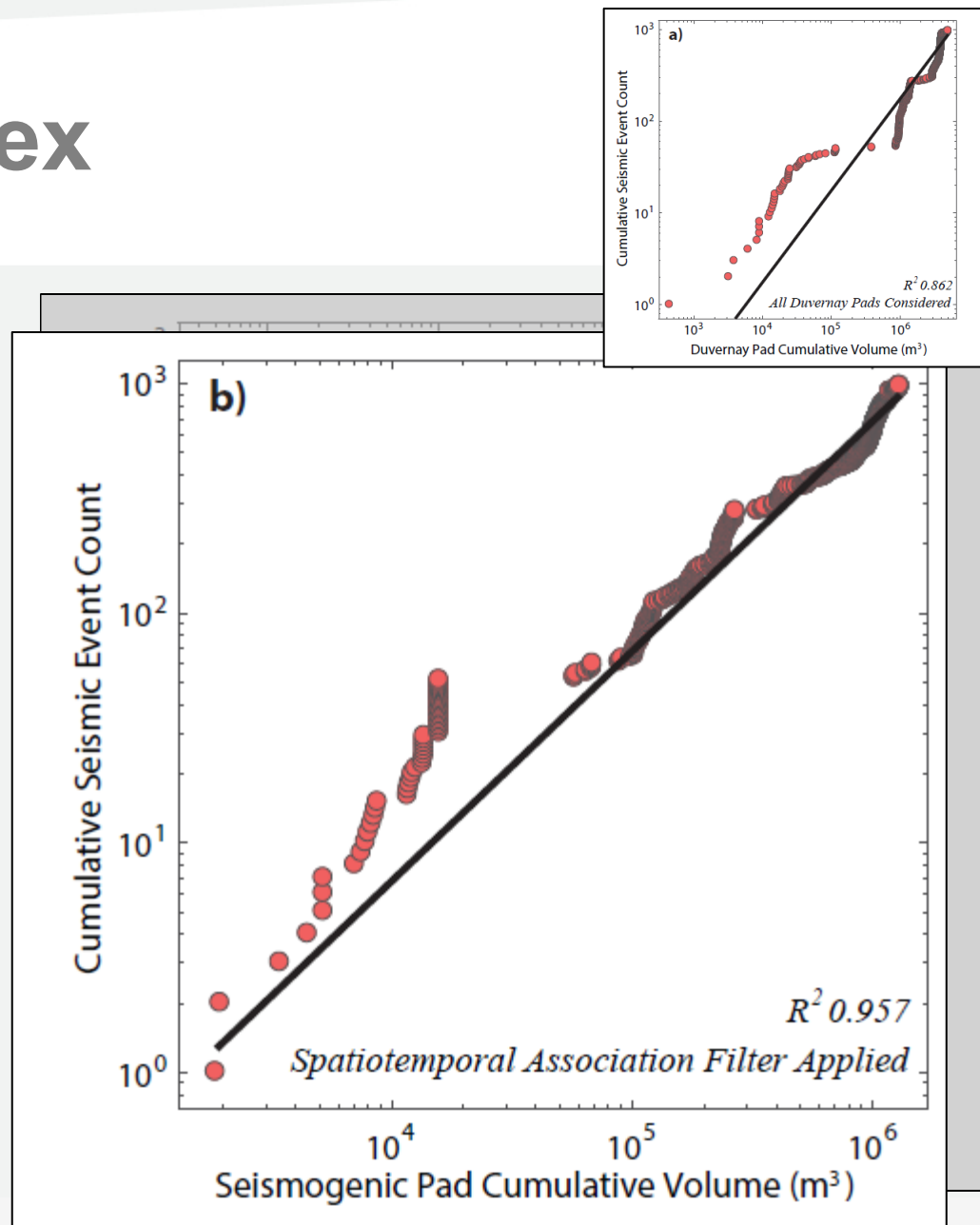


Rate



Seismogenic Index

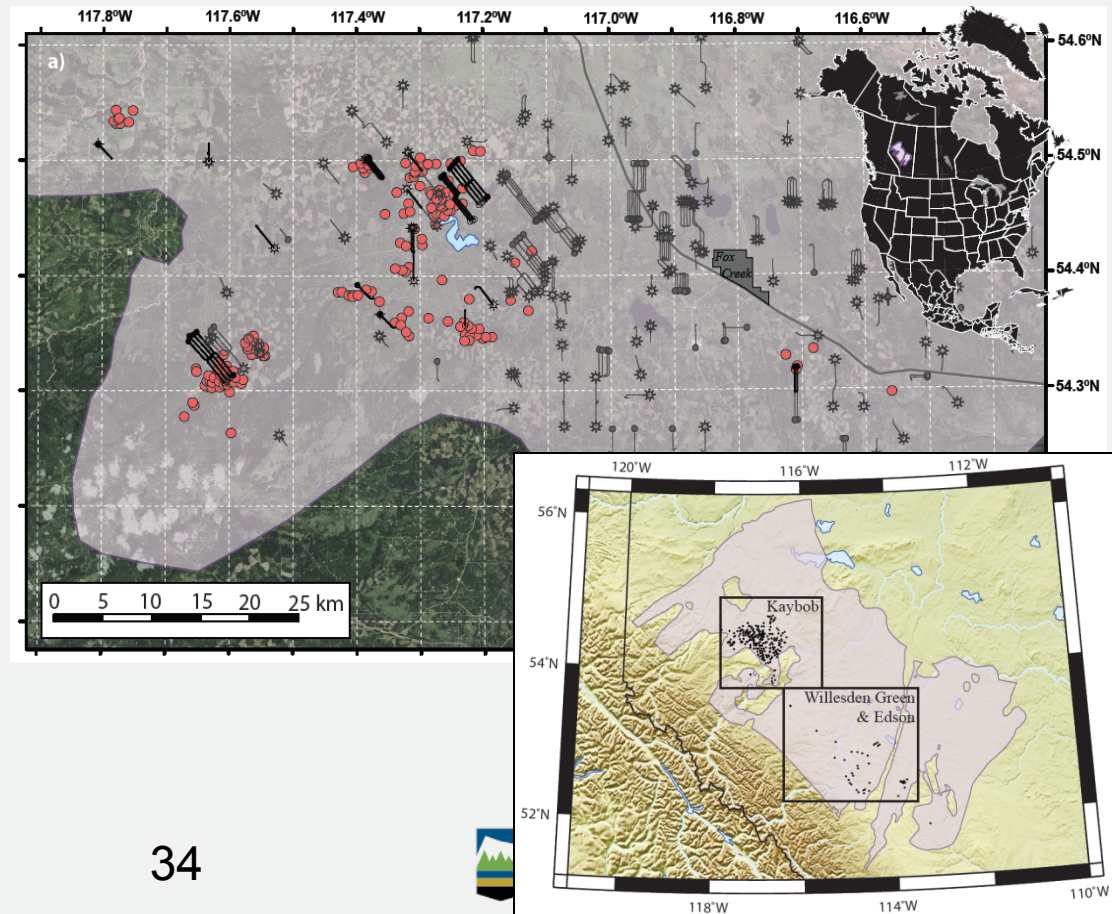
- Overall, decent linear fit to Σ data in Kaybob Duvernay.
- Noted systematic biases above or below best fit line.
- Biases not strongly pronounced in single cluster/pad Σ fits.
- Possible spatial trends?
- Significant improvement to goodness of fit (R^2 0.96) if only seismogenic wells are considered



Are the Spatial Trends Real?

- Spatial bias isn't an artifact of detection capabilities.
- δ is only allowed to have values of 1 or zero: turns seismicity on or off.
- SAF is a rudimentary and empirical estimate of δ (improves fit: R^2 0.96).
- δ represents the seismogenic activation potential: the likelihood that a well will induce an earthquake.

$$N \downarrow M = V(t) \cdot \delta(r) \cdot 10^{\uparrow \Sigma 10^{\uparrow - b} M}$$





Thank You



www.aer.ca
www.ag.s.aer.ca

Publications

- Schultz et al. (2014) An investigation of seismicity clustered near the Cordell Field, west central Alberta, and its relation to a nearby disposal well, JGR Solid Earth, 119, 3410-3423, doi:10.1002/2013JB0100836
- Schultz et al. (2015) Detection threshold and location resolution of the Alberta Geological Survey Earthquake Catalogue, SRL, V 86, N 2A, doi: 10.1785/0220140203
- Schultz et al. (2015) The Cardston earthquake swarm and hydraulic fracturing of the Exshaw formation (Alberta Bakken Play), BSSA, V 105, N. 6, doi: 10.1785/0120150131
- Schultz et al. (2015) Hydraulic fracturing and the Crooked Lake Sequences: insights gleaned from regional seismic networks, GRL, 42, doi: 10.1002/201GL063455
- Wang et al. (2016) Source analysis of a potential hydraulic-fracturing-induced earthquake near Fox Creek, Alberta, GRL, 43, doi:10.1002/2015GL066917
- Schultz et al. (2016) Linking fossil reefs with earthquakes: geologic insight to where induced seismicity occurs in Alberta, GRL, 43, doi: 10.1002/2015GL067514
- Schultz et al. (2017) A seismological overview of the induced earthquakes in the Duvernay play near Fox Creek, Alberta, JGR: Solid Earth, 122, doi: 10.1002/2016JB013570
- Schultz et al. (2018) Hydraulic fracturing volume is associated with induced earthquake productivity in the Duvernay play, Science, 359, doi: 10.1126/science.aao0159
- Pawley et al. (2018) The geological susceptibility of induced earthquakes in the Duvernay play, GRL, 45, doi: 10.1002/2017GL076100
- Corlett et al. (2018) Subsurface faults inferred from reflection seismic, earthquakes, and sedimentological relationships: implications for induced seismicity in Alberta, Canada, MPG, doi: 10.1016/j.marpetgeo.2018.03.008