Hydraulic fracturing induced earthquakes in western Canada

Yajing Liu[1], Rebecca Harrington[2], Honn Kao[3,5], Andres Peña Castro[1], Kai Deng[4], John Onwuemeka[1], Marco Roth[2], Alessandro Verdecchia[1], Ricarda Wache[2], Bei Wang[3,5], Hongyu Yu[3], Yong Zhang[6]

1. McGill University
2. Ruhr University Bochum
3. Pacific Geoscience Centre, Geological Survey of Canada
4. Chengdu University of Technology
5. University of Victoria
6. Peking University

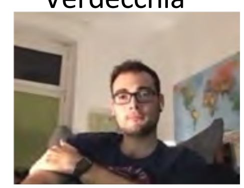
With support from BC Oil and Gas Commission (Stu Venables)
Fieldwork led by McGill (Greg Langston)


Rebecca Harrington

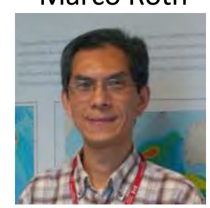

Alessandro Verdecchia


Andres Peña-Castro

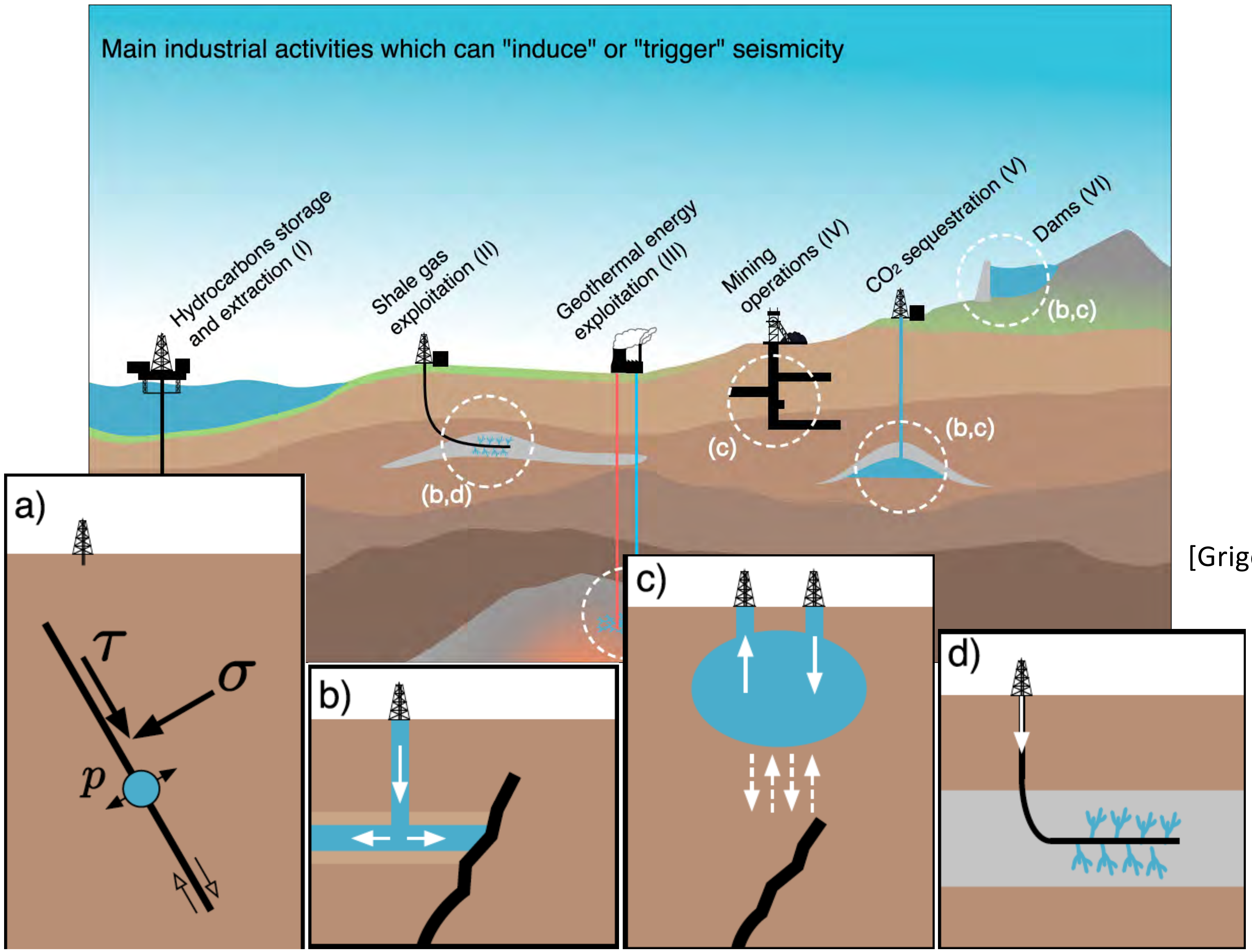

Hongyu Yu


Marco Roth


John Onwuemeka

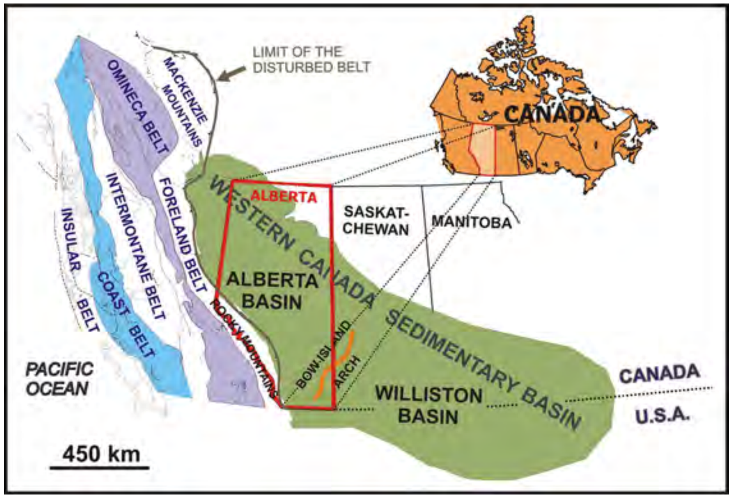

Honn Kao

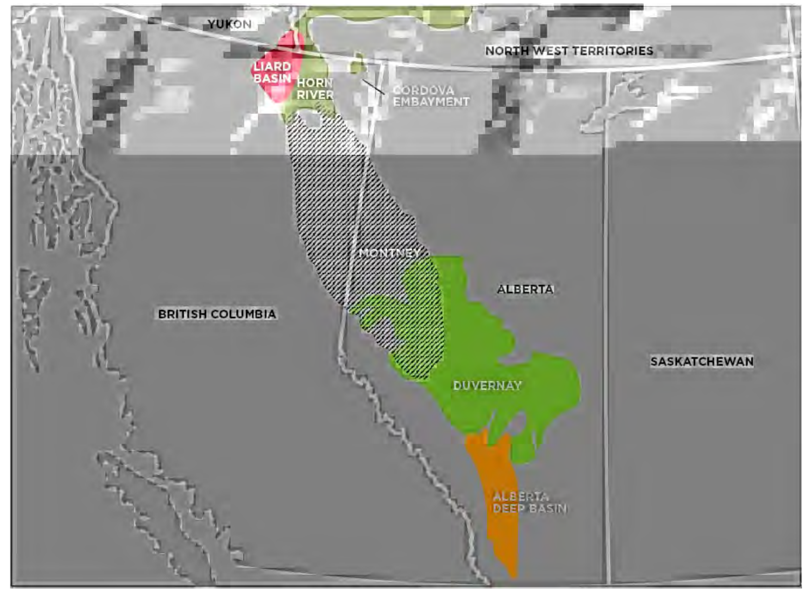
CUHK
13 November 2020



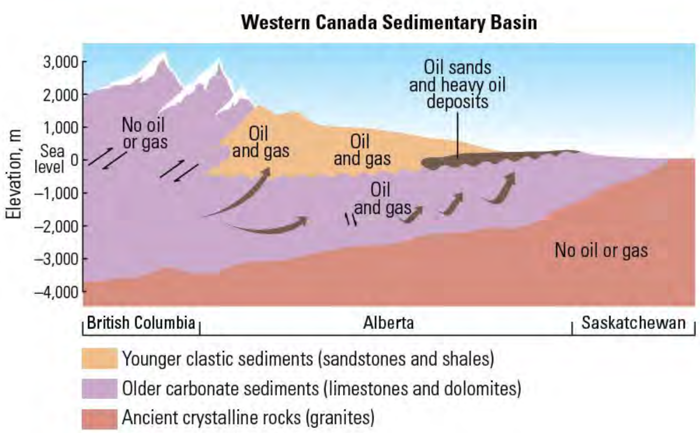
[Grigoli et al., 2017]

Western Canada Sedimentary Basin

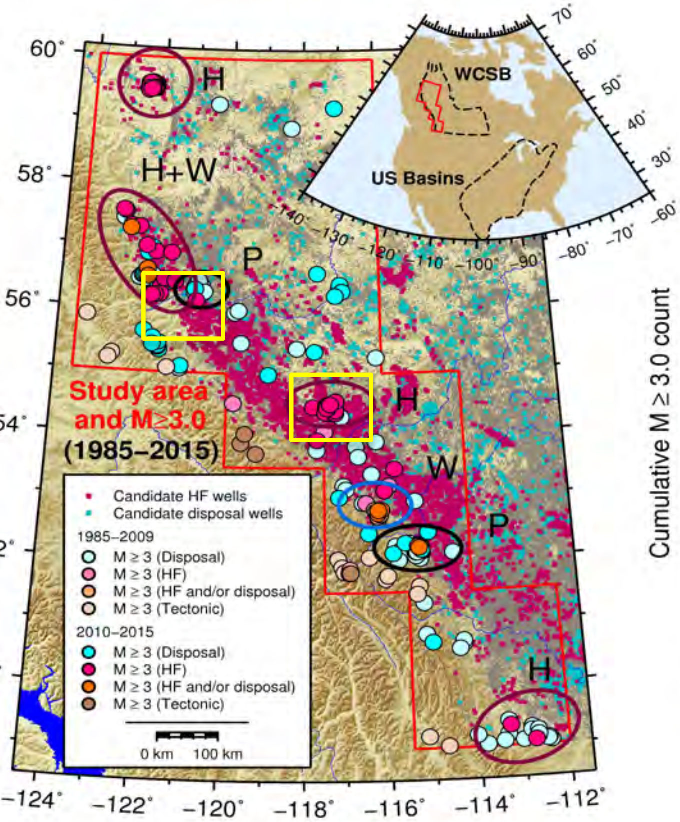


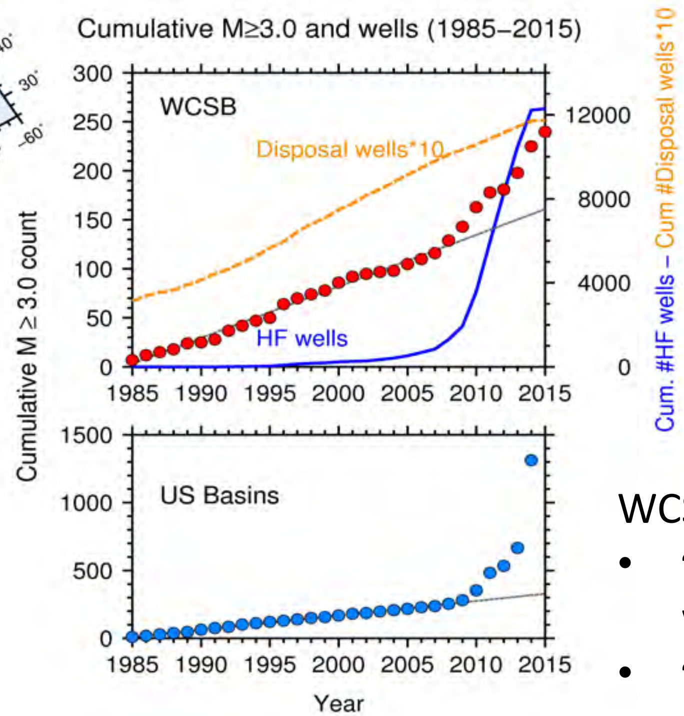


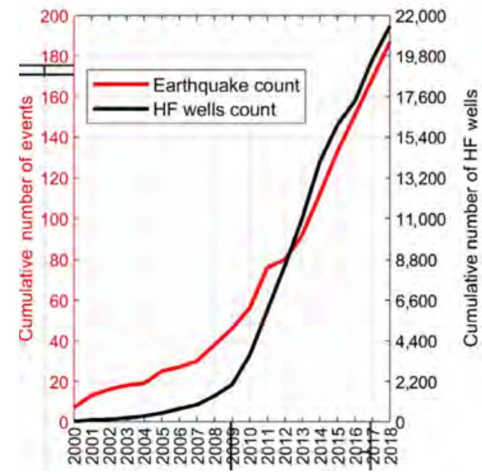
[CAPP]



Seismicity and wells in WCSB







[Atkinson et al., 2016; Ghofrani and Atkinson, 2020]

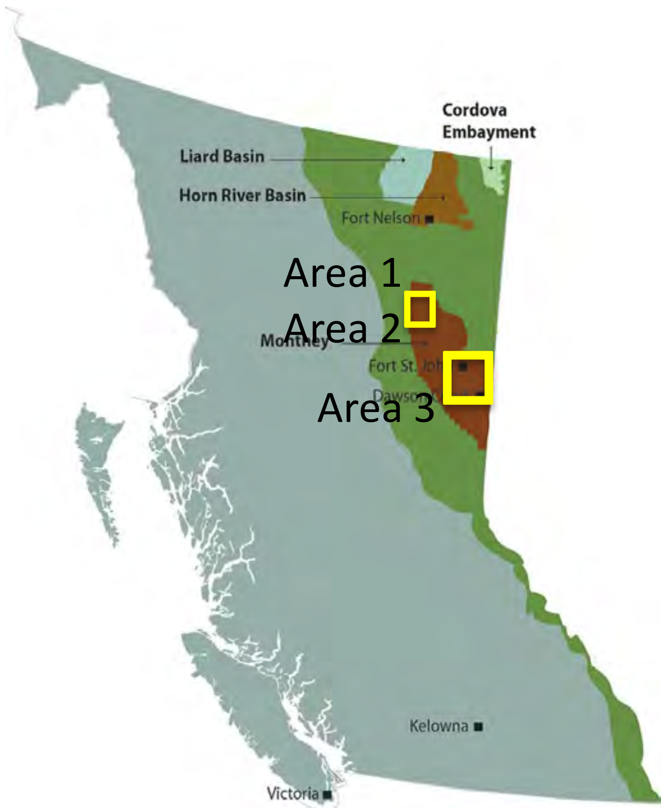
WCSB on average:

- ~0.3% of HF wells associated with M3+ (1985-2014)
- ~0.8% (2009-2019)
- varies by a factor of ~10 for different formations

Outline

- High-resolution seismicity catalog – identification of spatial and temporal correlation with fluid injection
- Source parameter inversion for induced earthquakes in the Western Canada Sedimentary Basin – differences in induced vs. tectonic earthquakes
- Poroelastic stress and fault slip modeling for earthquakes linked to fluid injection – optimize operation parameters to minimize seismic hazard

Induced seismicity monitoring in northeast BC

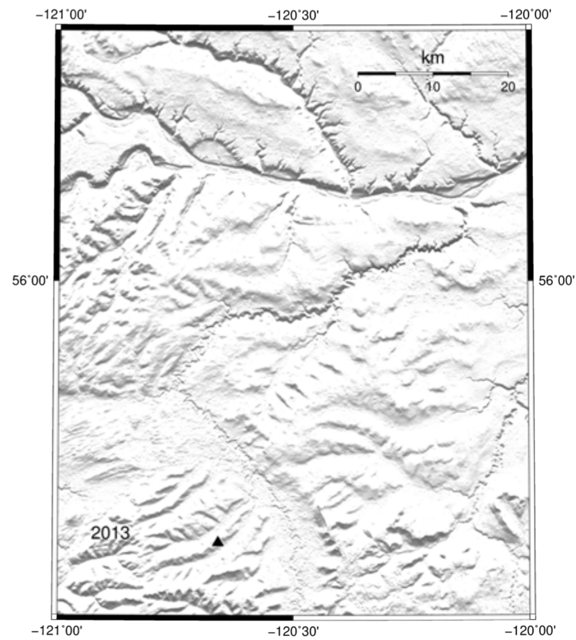


[BC Oil and Gas Commission]

Deployments:

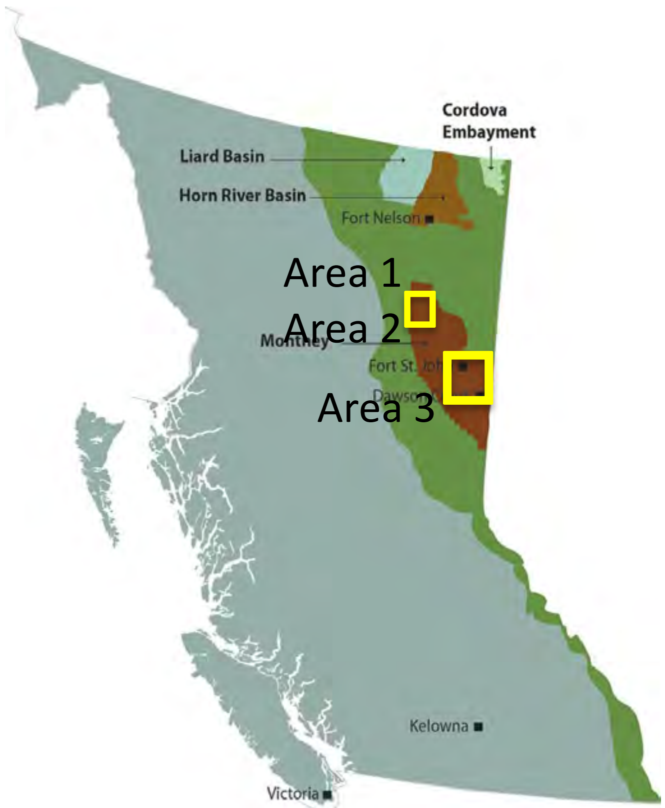
1. May – Oct 2015 [Yu et al., 2019; 2020; Wang et al., 2019, 2020]
2. Jun – Oct 2016
3. Jul 2017 – Present [Peña-Castro and Roth, et al, 2020; Roth et al., 2020]

Station coverage in Kiskatinaw area



IRIS network codes:
CN+1E
XL
EO

Induced seismicity monitoring in northeast BC



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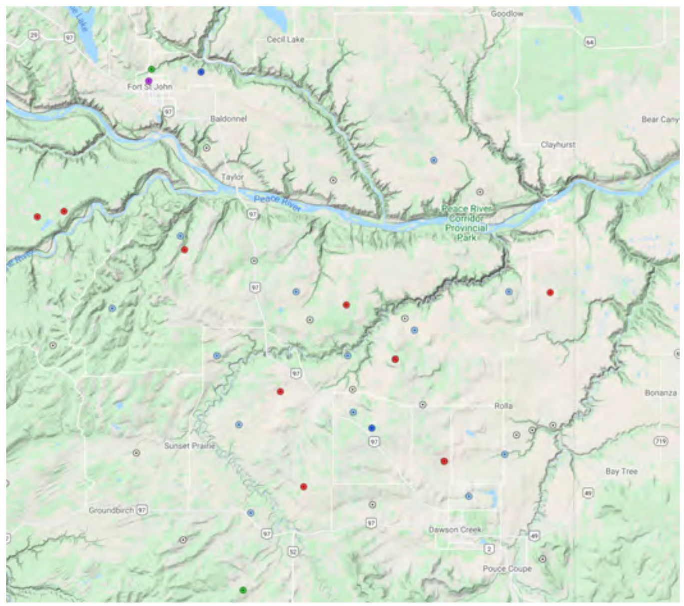

http://ds.iris.edu/gmap/

CN: NBC4/7: 2013/03-
1E: MONT1-9: 2018/10-
XL: MG01-10: 2017/07-
XL: RU01-06: 2019/07-
EO: KSW01-13: 2020/03-

Induced seismicity monitoring in northeast BC

MG01 Photo credit: G. Langston

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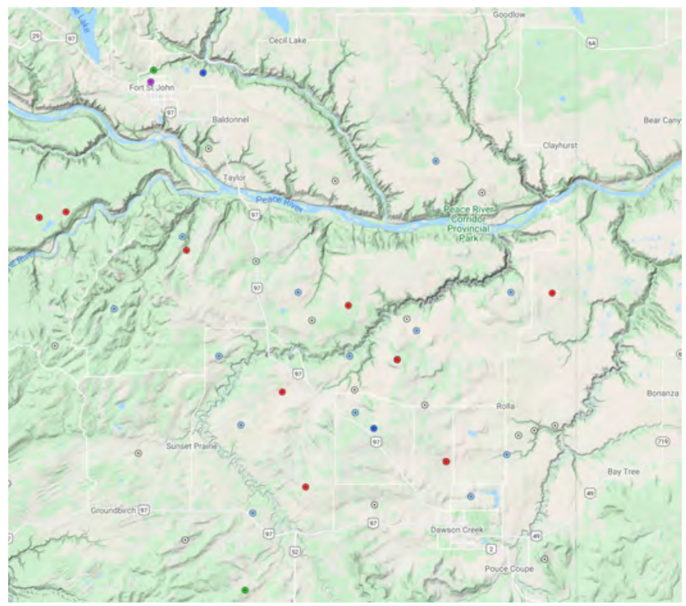

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1E: MONT1-9: 2018/10-
XL: MG01-10: 2017/07-
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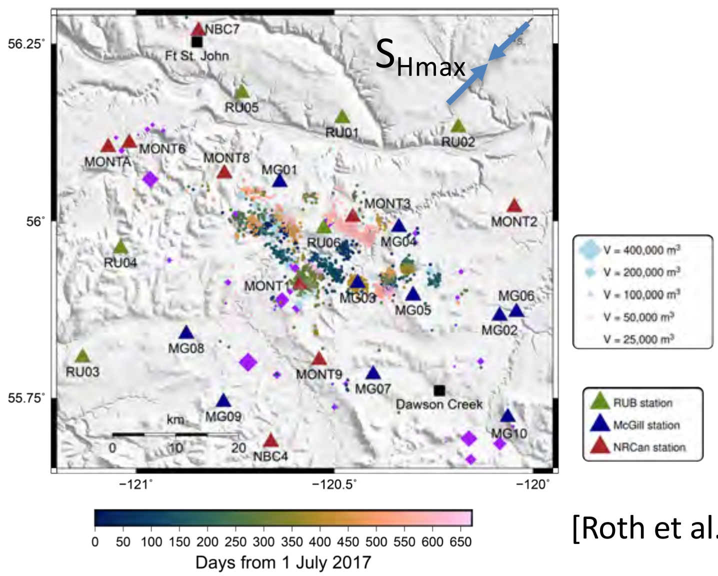
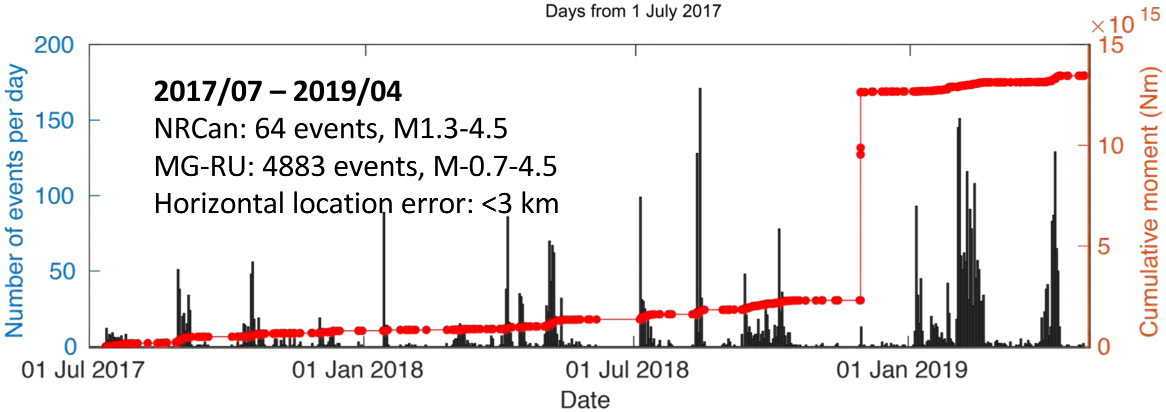
EO: KSW01-13: 2020/03-

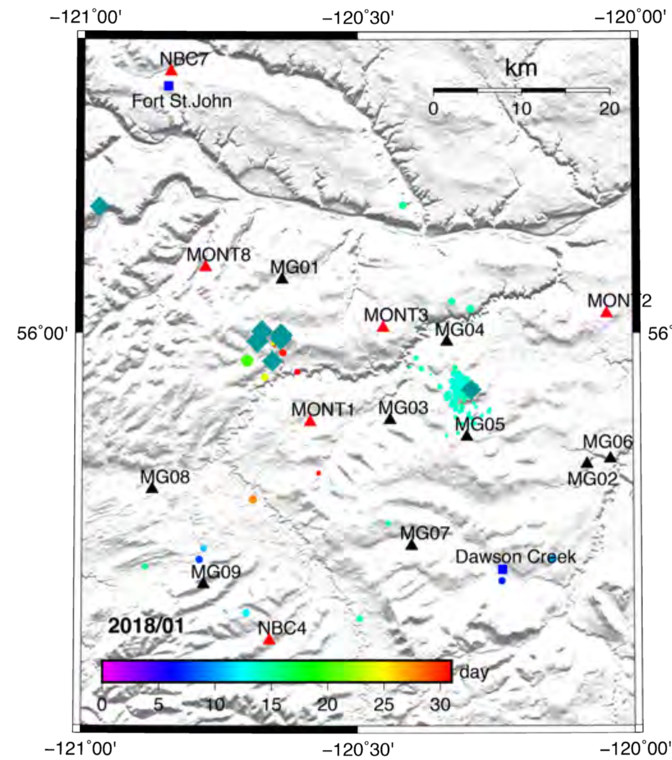
Seismicity monitoring in Kiskatinaw (Dawson Creek-Septimus) area



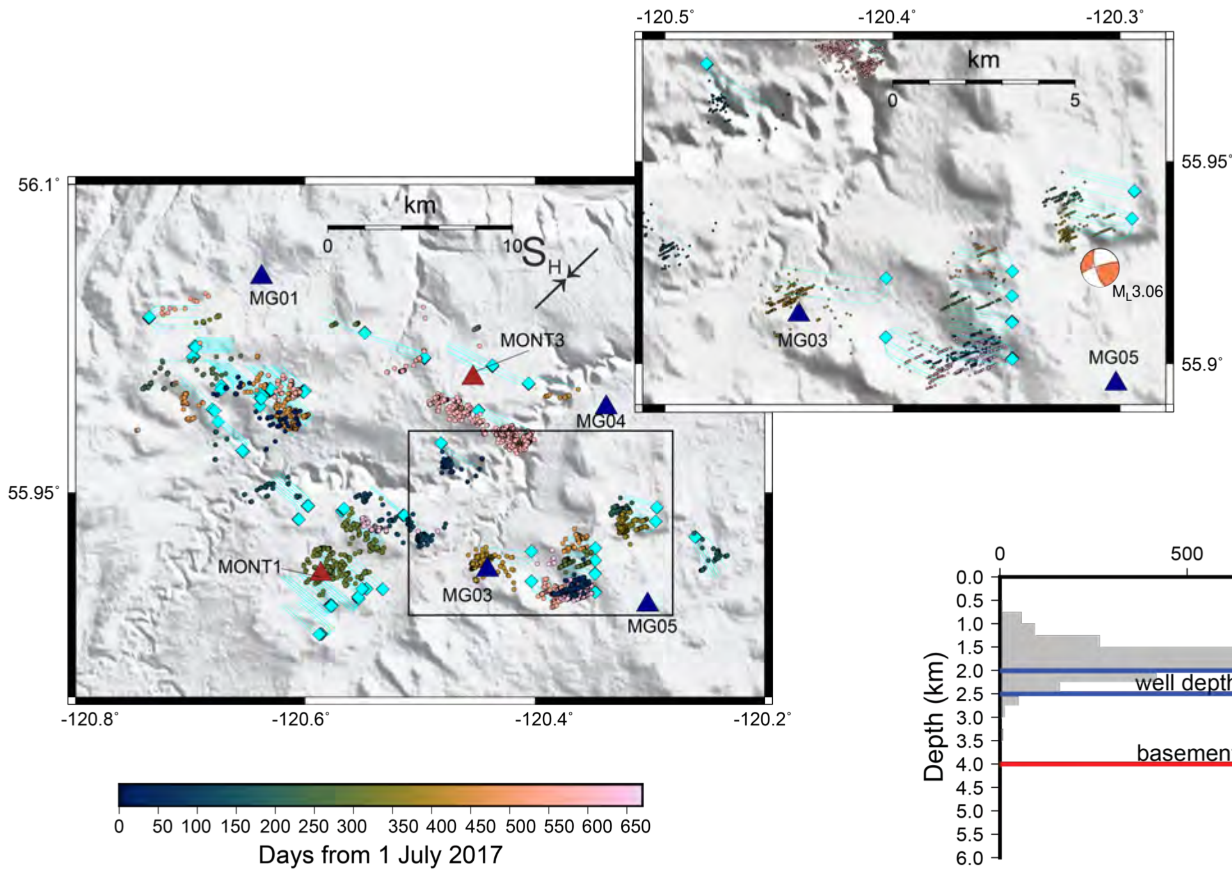
[Roth et al., 2020]



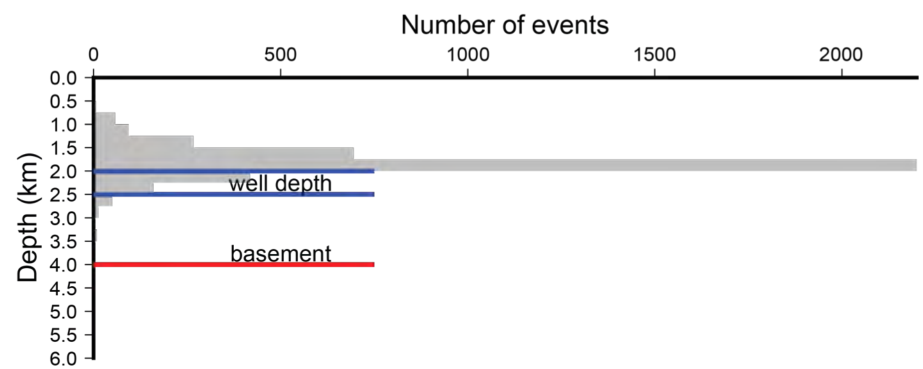
2018 monthly seismicity



Relocated seismicity

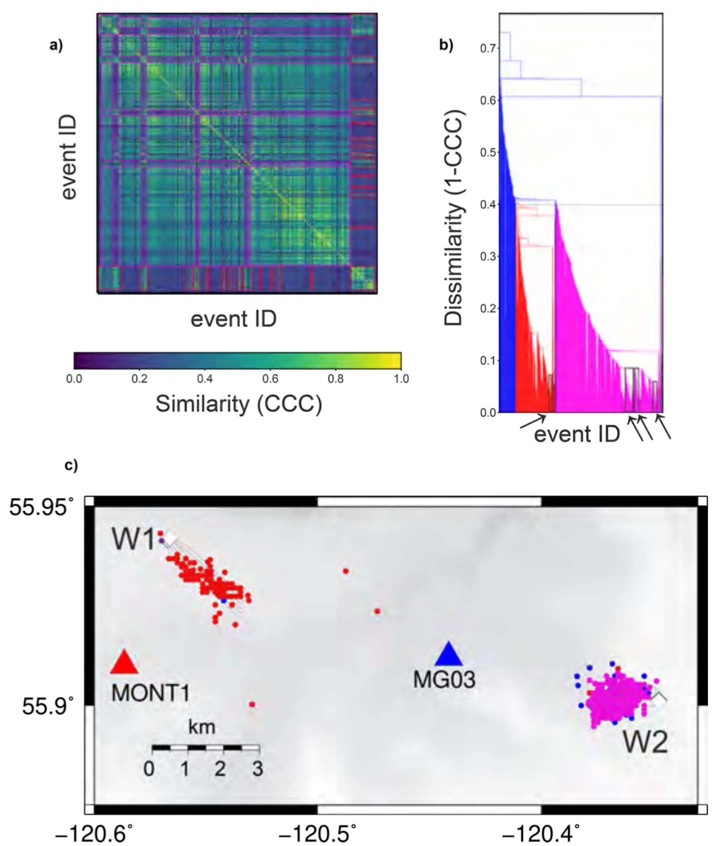


HypoDD: 4191 relocated out of 4883;
Relocation error: horizontal 13 +/- 28 m; vertical 29 +/-59 m
Most events are located around/above horizontal wells

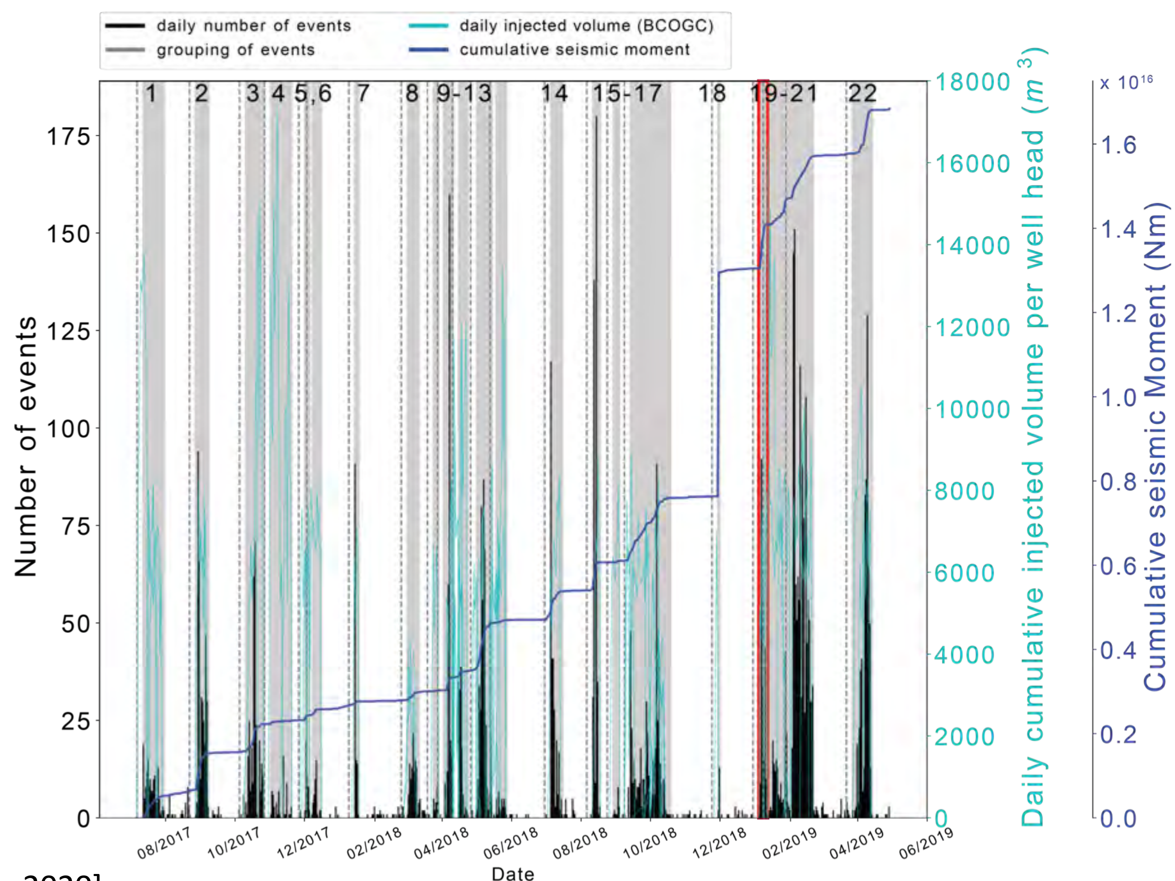


Fluid injection, seismicity and clustering

event *families (spatial)*



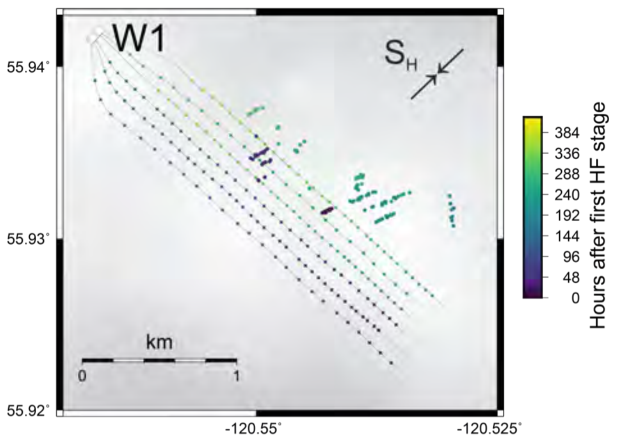
event *groups (temporal)*



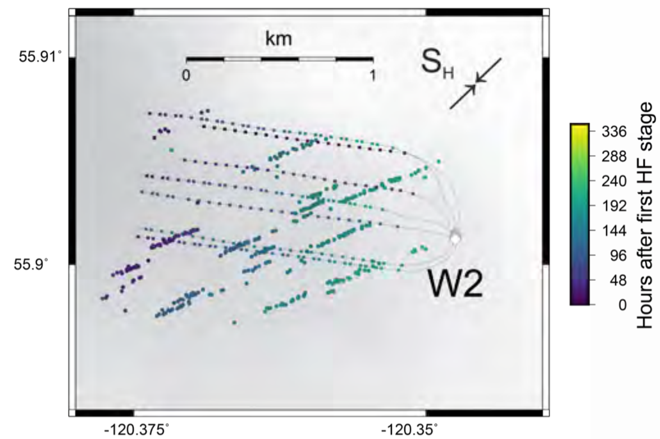
[Roth et al., 2020]

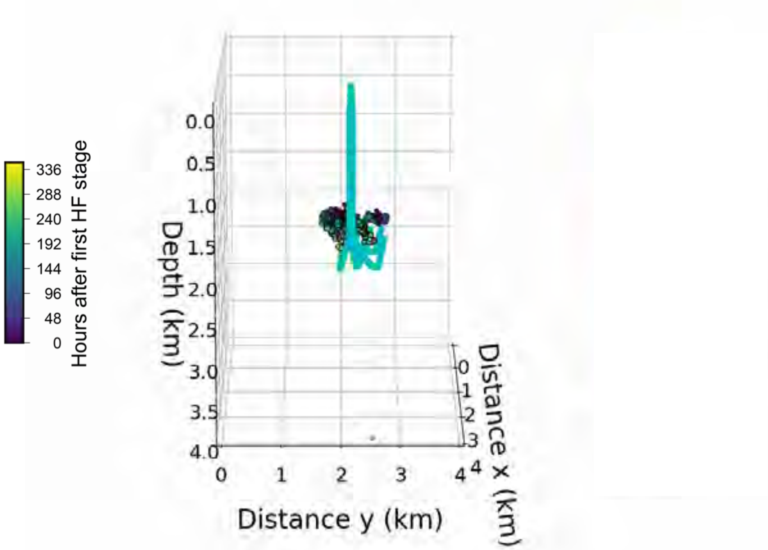
Relocated event *families*

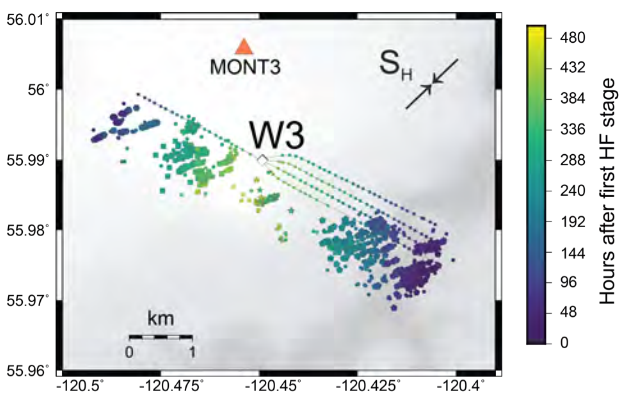
a)



b)

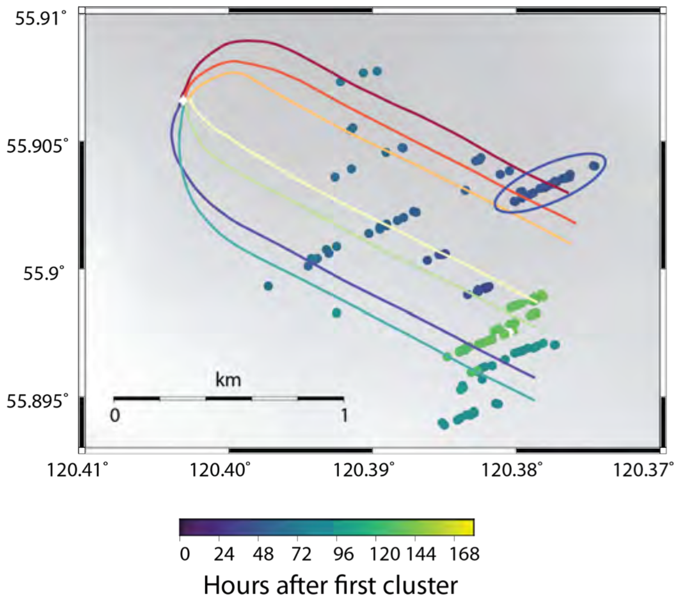


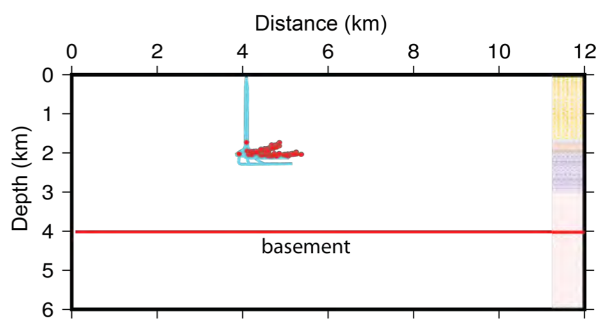


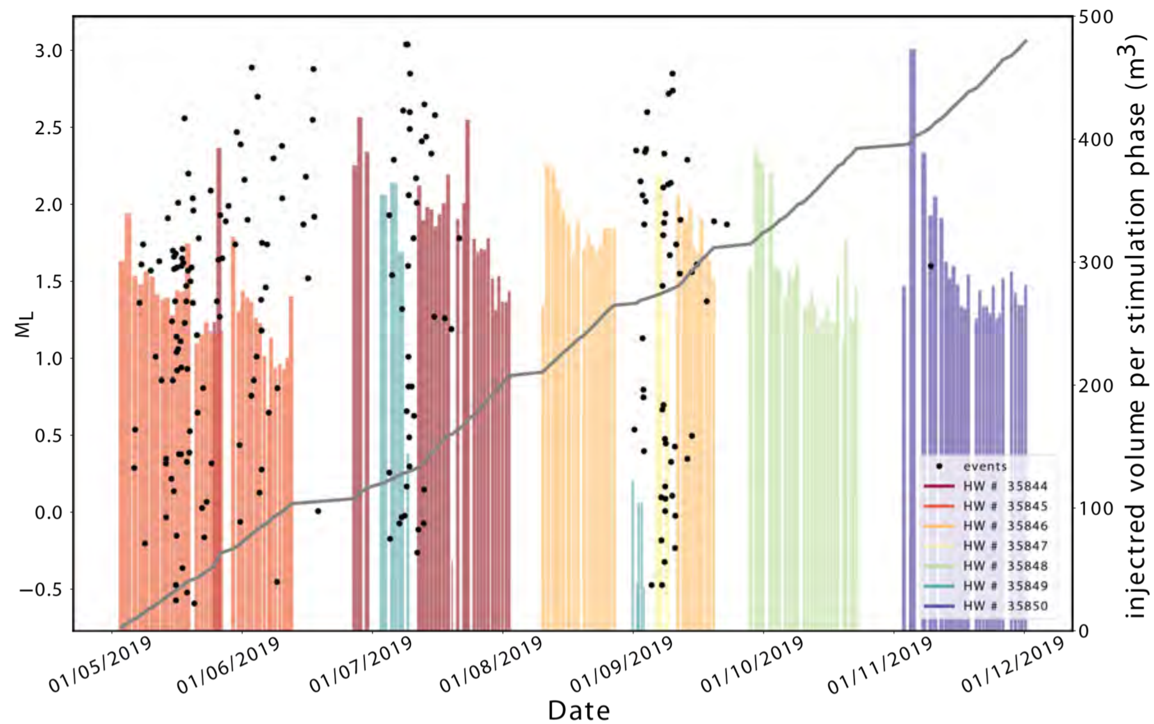


Linear alignments at small angle to S_{Hmax} ;
Cluster around horizontal well depth;
Temporal correlation with stimulation stages

Relocated clusters and correlation to stimulation stages







81% (163/202) of the events occur during ongoing well stimulation

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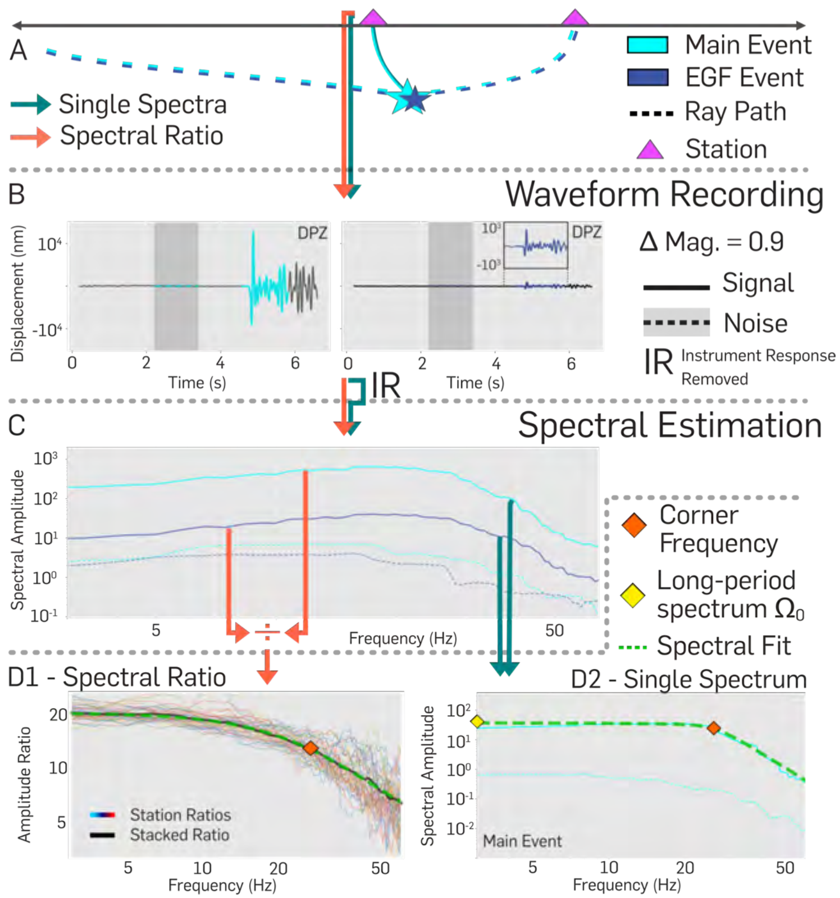
Stress drop estimates – spectral ratio analysis



Taking the spectral ratio of *main/eGF* effectively cancels effects of path, site and instrument responses, and only leave differences in sources.

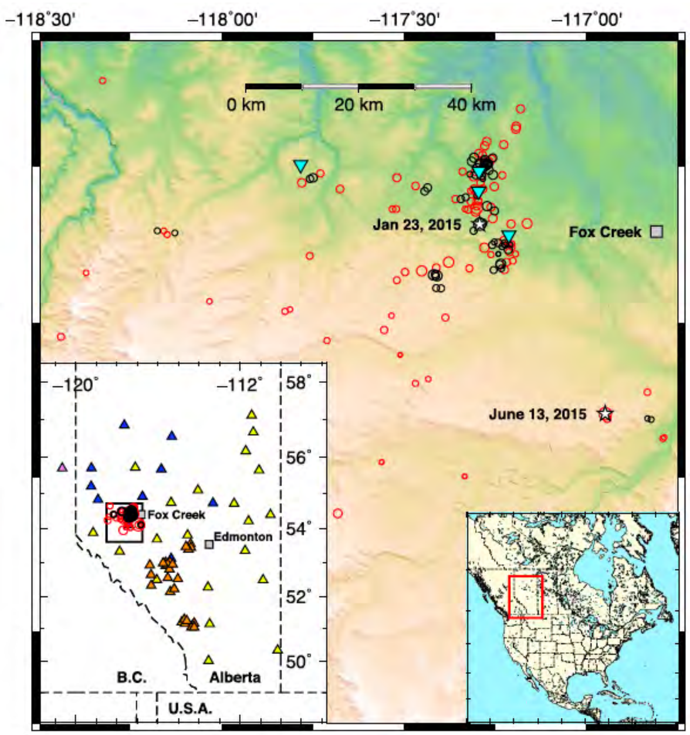
$$\Omega_1(f) = S_1(f) * P_1(f) * I_1(f)$$

$$\Omega_2(f) = S_2(f) * P_2(f) * I_2(f)$$

$$\frac{\Omega_1(f)}{\Omega_2(f)} = \frac{S_1(f)}{S_2(f)}$$

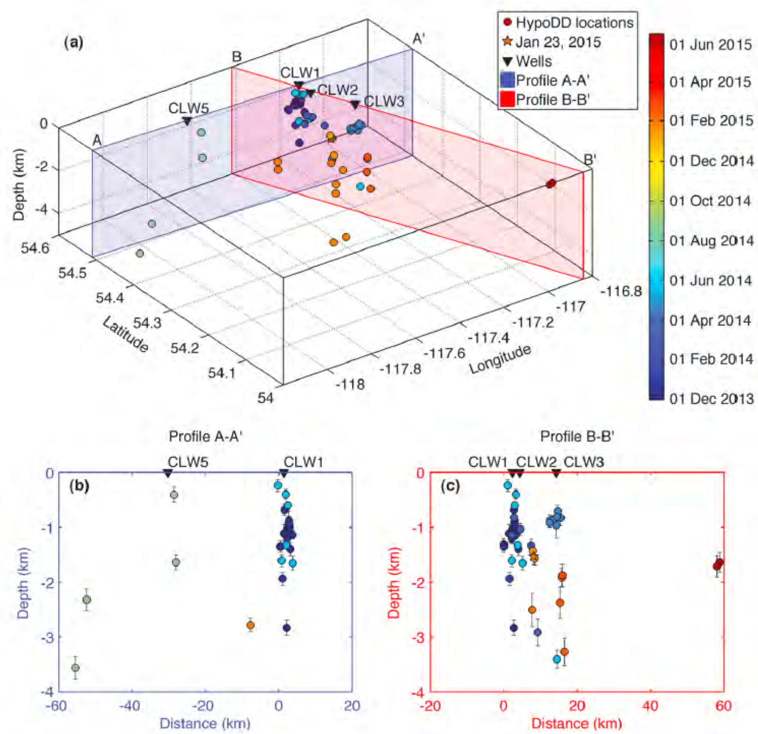
[Kemna et al., in prep; Abercrombie, 2015; Harrington et al., 2015, etc.]

Fox Creek HF induced sequence 2013-2015

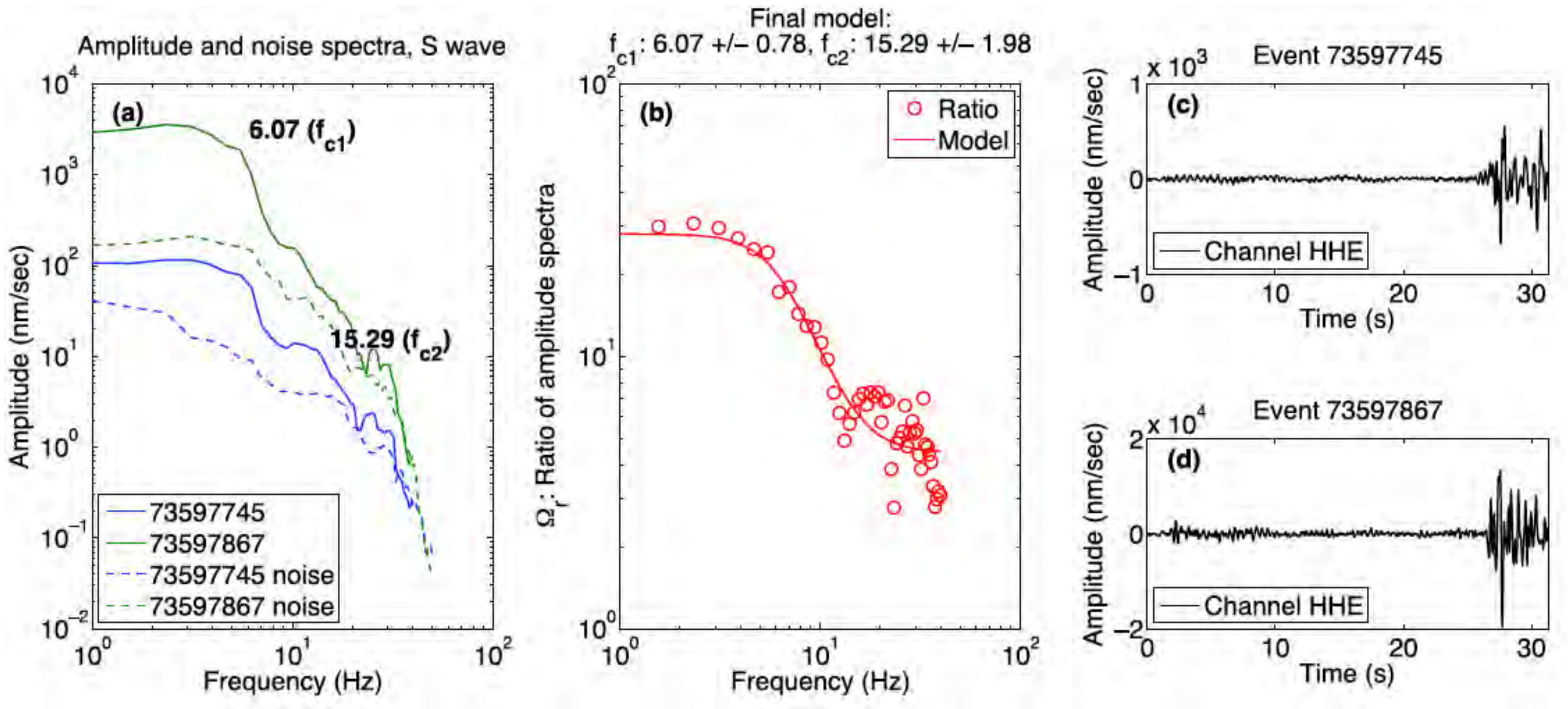


[Clerc et al., 2016]

After relocation

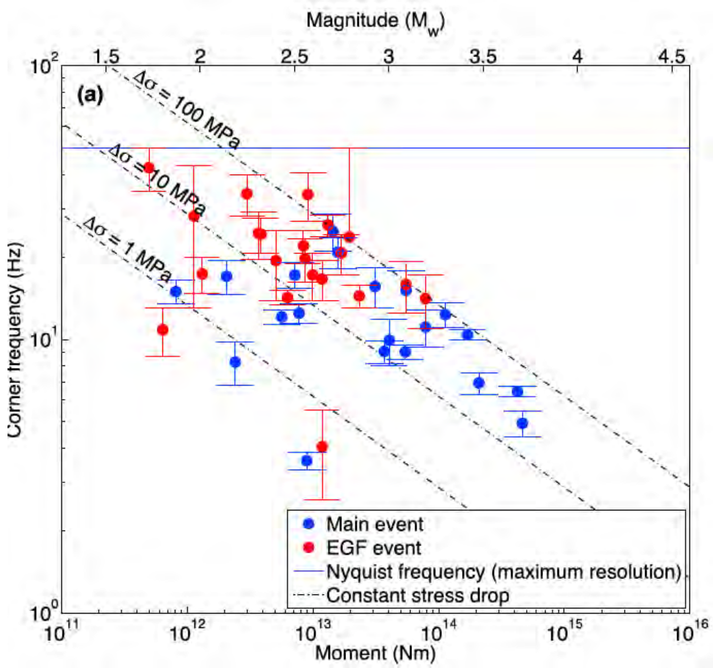


Stress drop estimates – Spectral ratio analysis

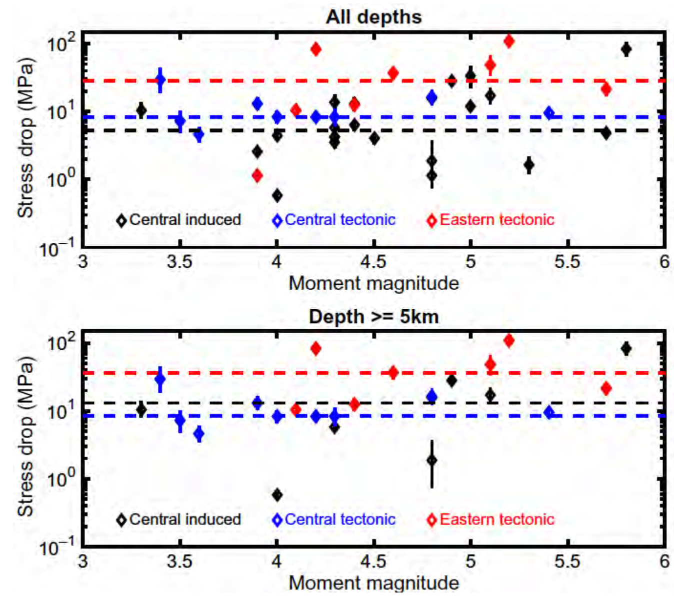


[Clerc et al., 2016]

Stress drop estimates – Spectral ratio analysis



[Clerc et al., 2016]

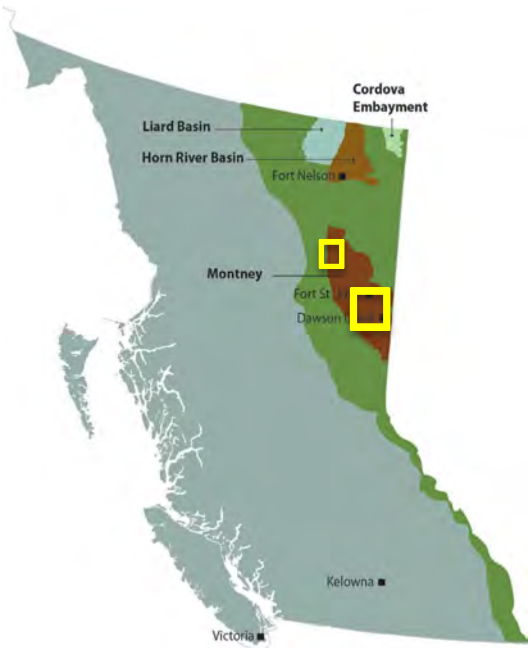


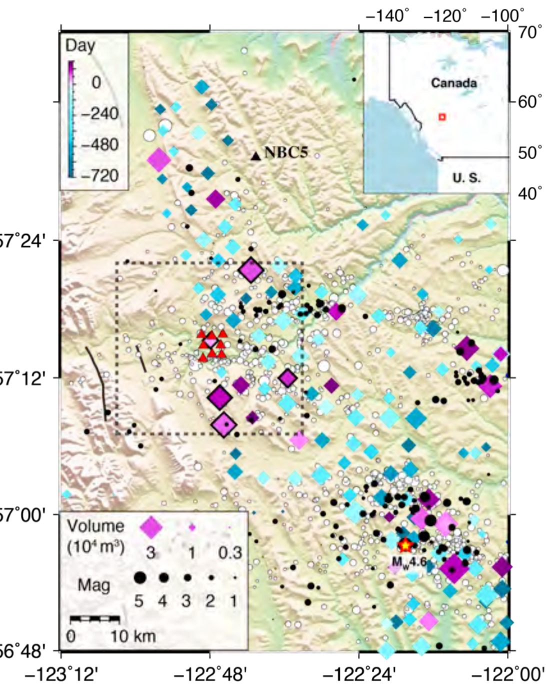
[Huang et al., 2017]

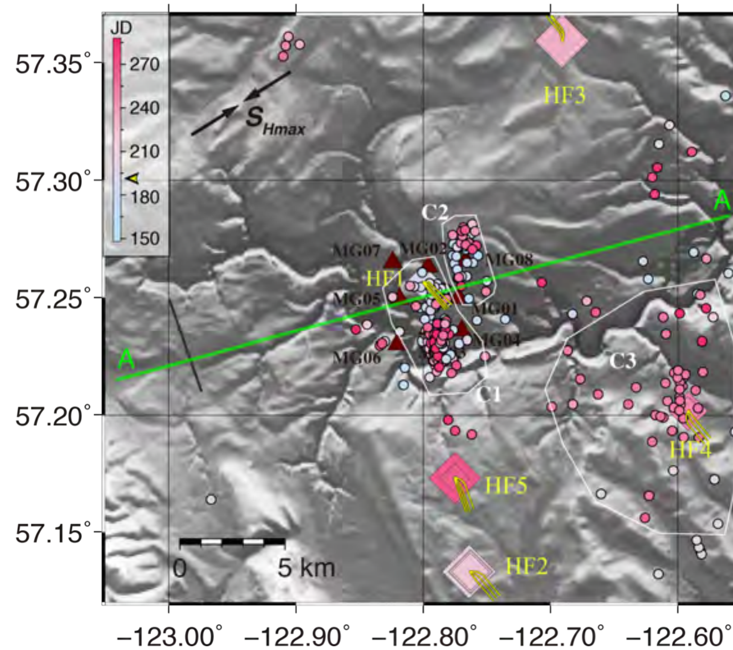
Stress drops of induced and tectonic earthquakes in the central United States are indistinguishable

Yihe Huang,[1]* William L. Ellsworth,[2] Gregory C. Beroza[2]

Case study with a local/dense array



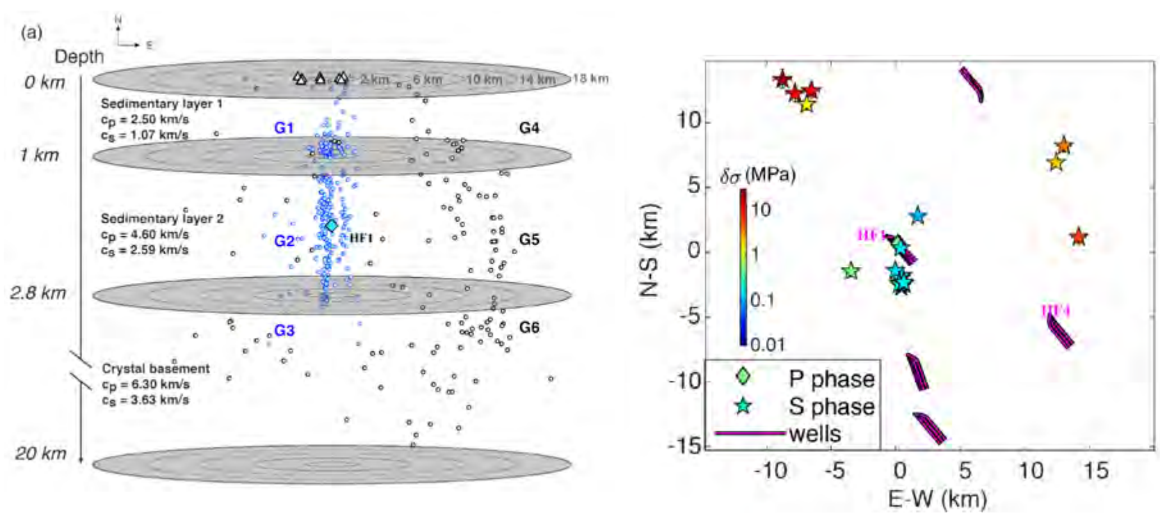


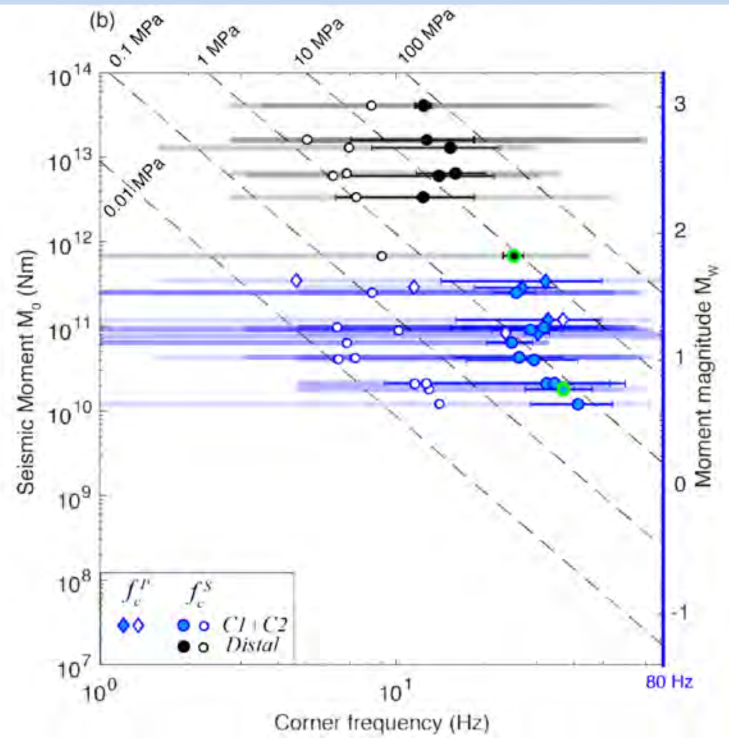


[Yu et al., 2019]

8 broadband stations at ~ 1 km spacing, covering pre-, co-, post-HF stimulation at 5 wells, May – October 2015.

Spatial variation of stress drops and Q





[Yu et al, 2020]

- Stress drop values of the ~480 (M<3) HF-induced earthquakes are within the range (1-100 MPa) for tectonic earthquakes. Similar values estimated for two M4+ sequences near Fort St John [Wang et al., 2020; Peña-Castro and Roth et all, 2020].
- Lower stress drops near the well – higher pore pressure
- Lower Q near the well – fractured rocks

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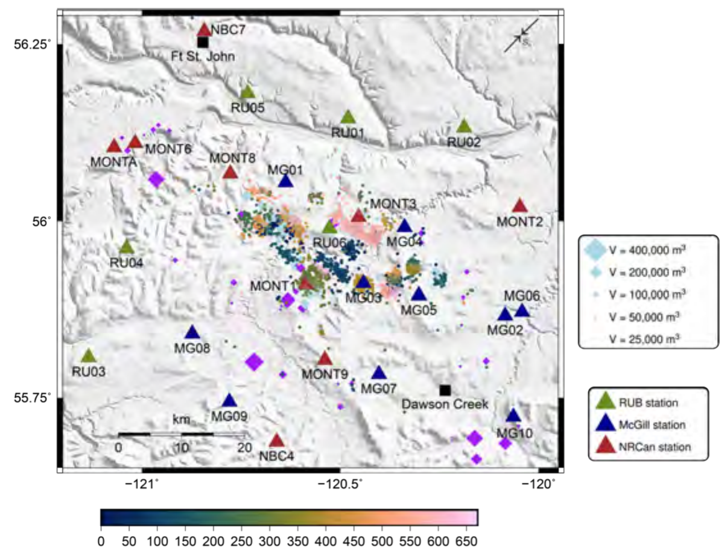
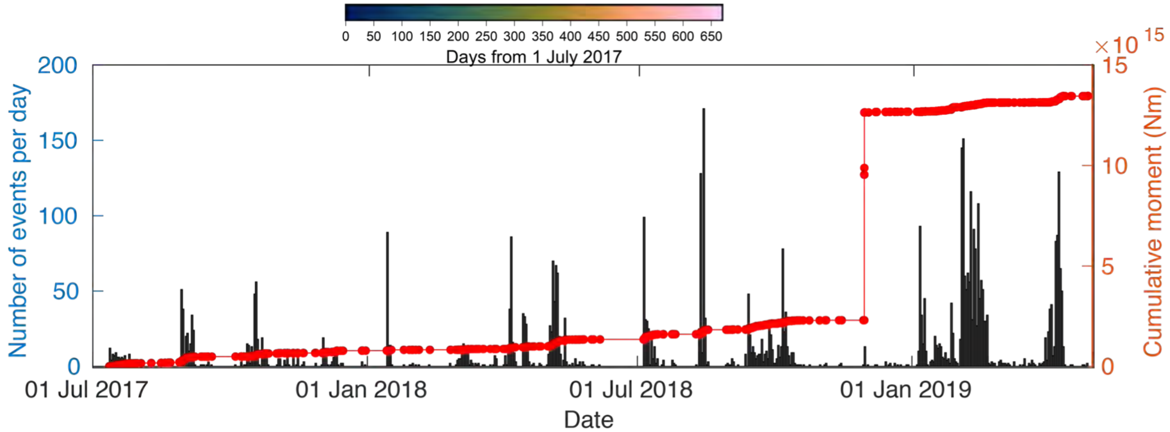
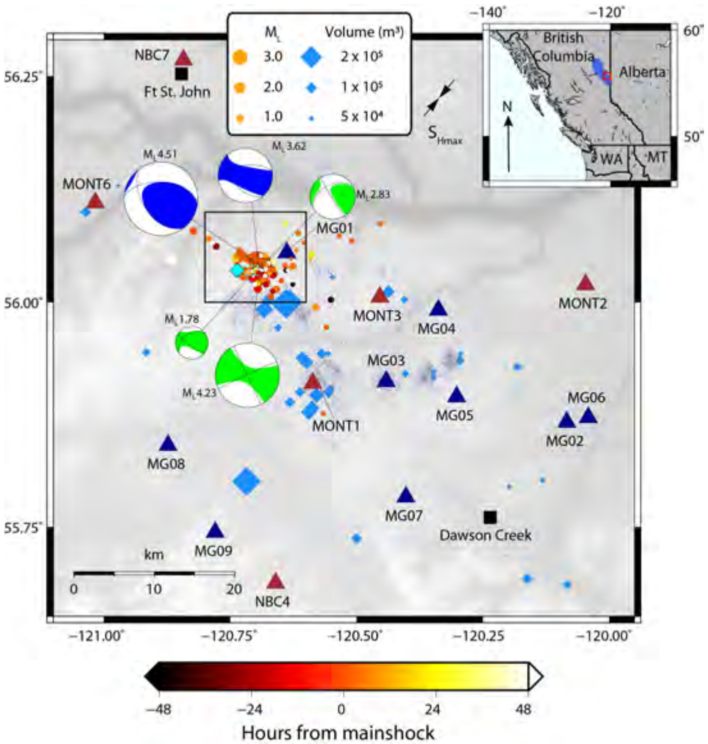
Seismicity in Kiskatinaw area



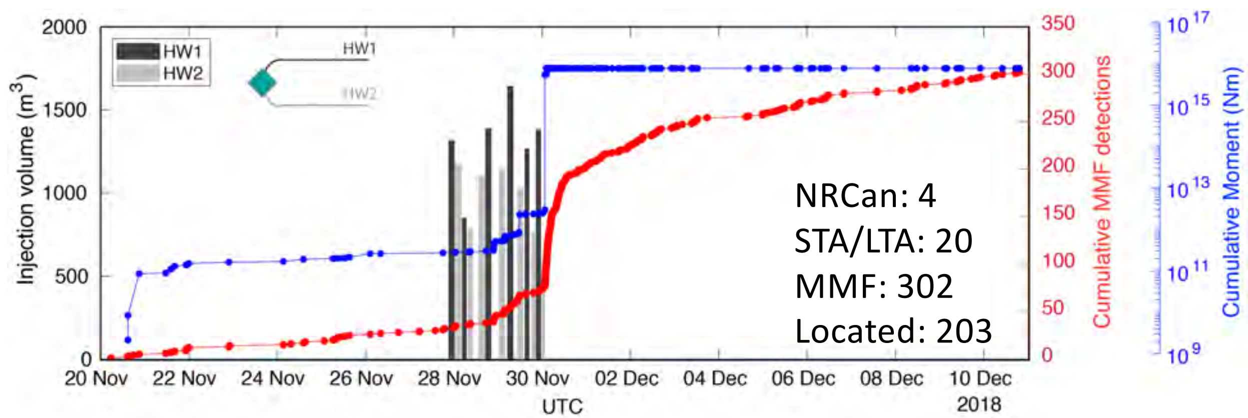
[Roth et al., 2020]



2018/11/30 M_L 4.5 sequence

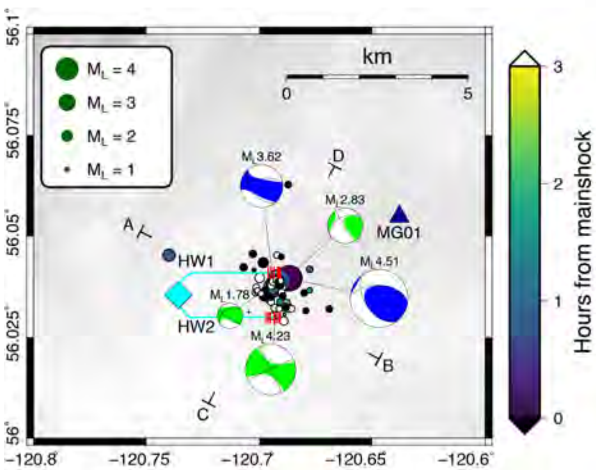


[Peña Castro, Roth, et al., 2020]

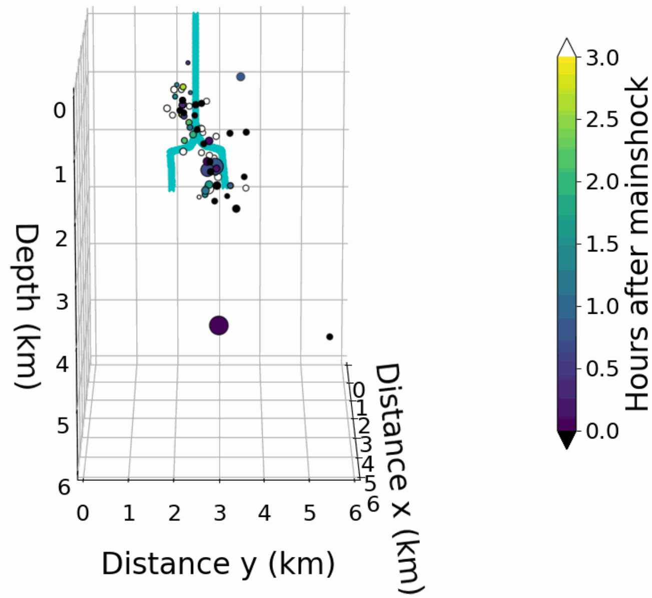


- Fluid injection in the Lower Montney (~2.3 km) along two horizontal wells for ~ 2 days (13 stages) prior to the M_L 4.5 mainshock, operation suspended afterward
- Use 7 template events (and the mainshock) for a multi-station matched-filter detection → 302 events ±10 days from the mainshock
- Use probabilistic source inversion *Grond* for full moment tensor solution → mainshock slip along NW-trending nodal plane, optimally oriented to regional S_{Hmax}
- Spectral estimates of static stress drop values → 1-10 MPa

2018/11/30 M_L 4.5 sequence



[Peña Castro, Roth, et al., 2020]



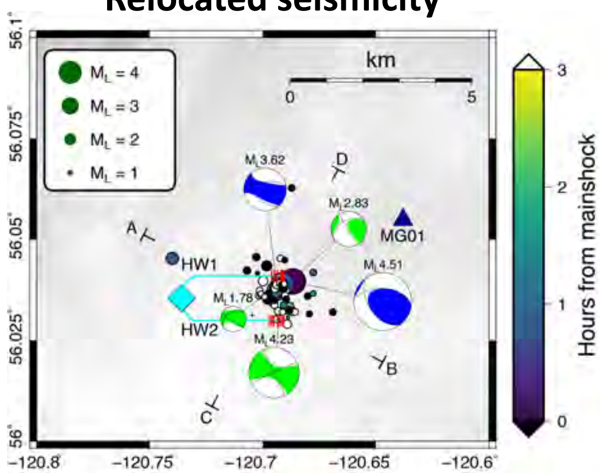
Earthquake relocation:

hypoDD (68): horizontal/vertical errors 60/80 m

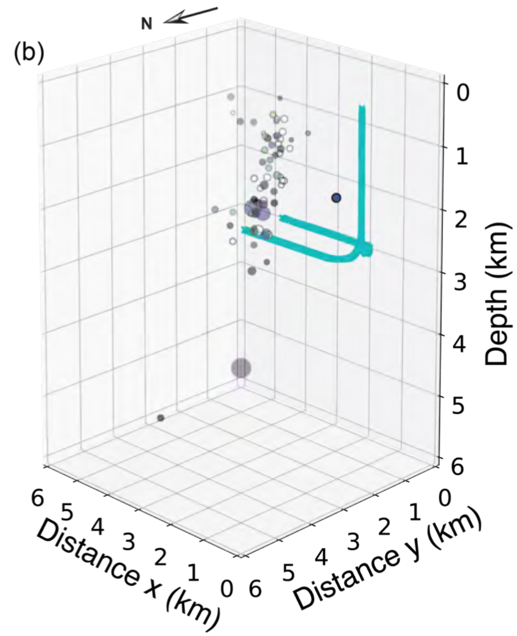
GrowClust (59): 520/450 m

2018/11/30 M_L 4.5 sequence

Relocated seismicity



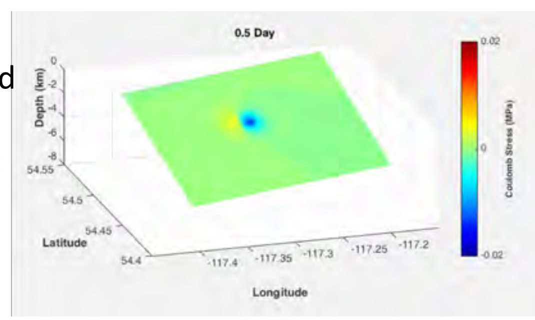
[Peña Castro, Roth, et al., 2020]

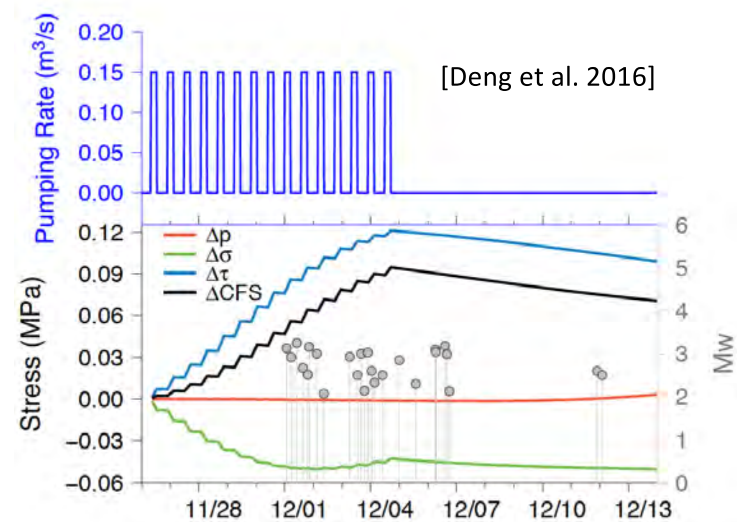


From injection source to mainshock hypocenter, **large spatial (2 km) but short temporal (2 days) separation** -> poroelastic stress triggering [e.g., Deng et al., 2016; Goebel et al., 2018]

hypoDD (68): horizontal/vertical errors 60/80 m
GrowClust (59): 520/450 m

December 2013 Crooked Lake (Alberta) induced seismicity sequence
Shear and normal stress changes are dominant over pore pressure change
Most seismicity occurred within positive Coulomb stress change regime.





Poroelastic stress model

Linear poroelasticity

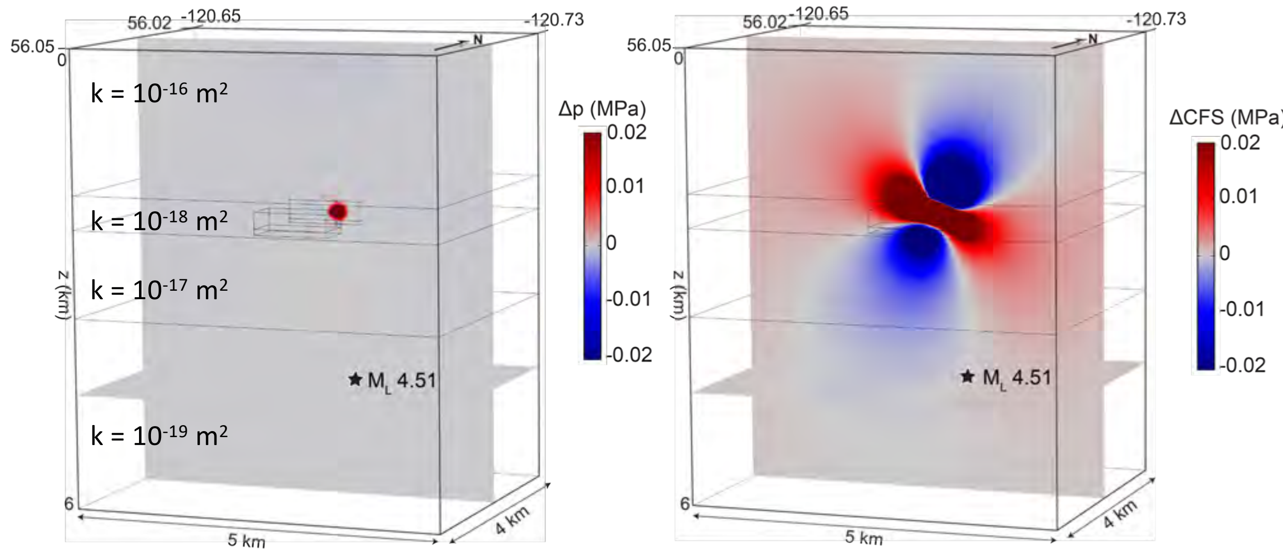
(*COMSOL Multiphysics*)

$$G\nabla^2 u + \frac{G}{1-2\nu}\nabla\varepsilon_{kk} - \alpha p = f(x,t)$$

$$\frac{1}{M}\frac{\partial p}{\partial t} + \alpha\frac{\partial \varepsilon_{kk}}{\partial t} - \nabla\cdot\left(\frac{\kappa}{\eta}\nabla p\right) = q(x,t)$$

$$\sigma_{ij} = \frac{2G\nu}{1-2\nu}\varepsilon_{kk} + 2G\varepsilon_{ij} - \alpha p\delta_{ij}$$

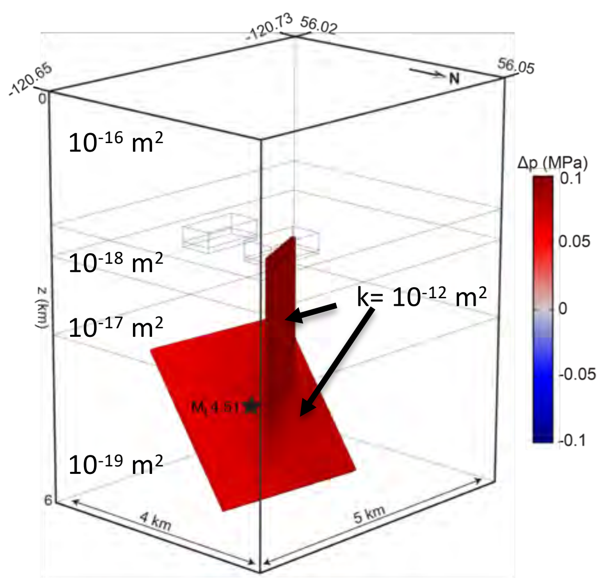
[Biot, 1941; Rice and Cleary, 1976]

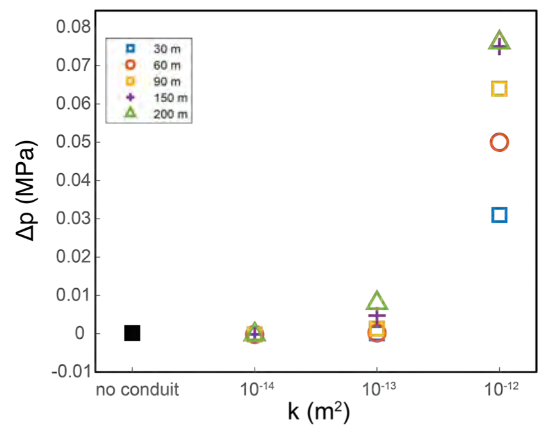


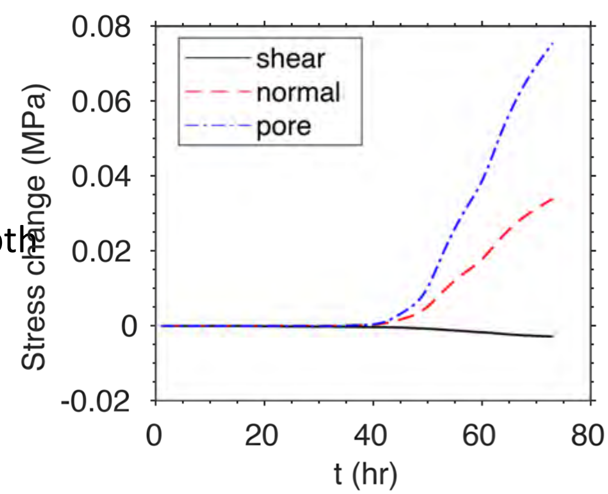
Without hydraulic conduits, pore pressure increase is negligible at the M_L 4.5 hypocenter. Coulomb stress change is ~ 1.5×10^{-4} MPa, 1-2 orders of magnitude lower than stress perturbation (~ 10kPa) of identified remote dynamic triggering in WCSB [Wang et al., 2015,. 2018].

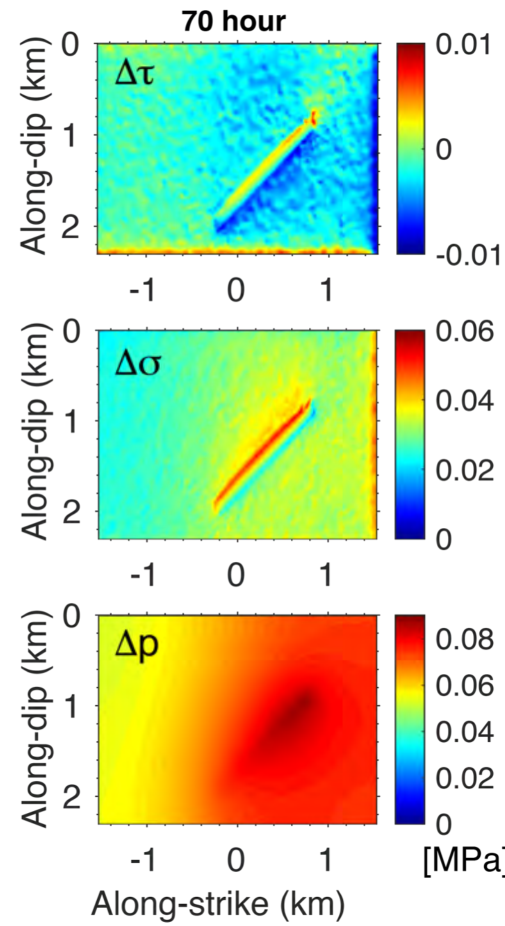
The isolated occurrence of the mainshock at ~ 4.5 km also suggests poroelastic stress triggering an unlikely mechanism.

Stress chatter #1: Rapid fluid diffusion along a hydraulic conduit









Introducing a high permeability conduit channeling fluids from the injection depth to the mainshock fault, pore pressure increase up to ~ 0.1 MPa.

Effective perturbation duration is ~ 32 hours (1.3 days).

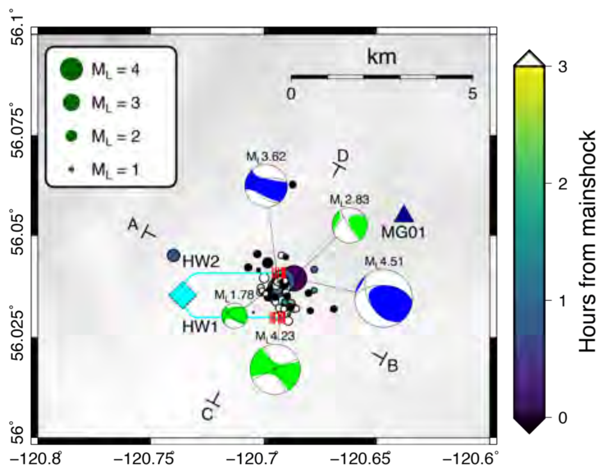
Stress “chatter” #2: earthquake-earthquake interaction

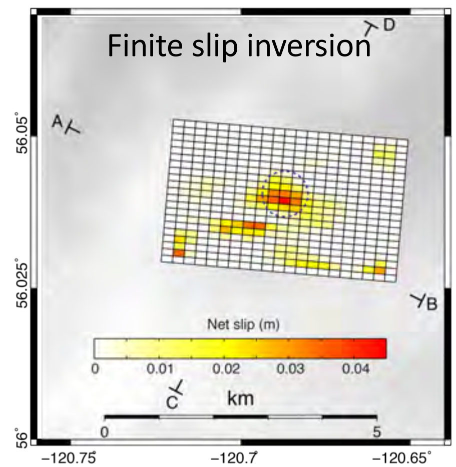
Static Coulomb stress change
due to the M_L 4.5 coseismic slip

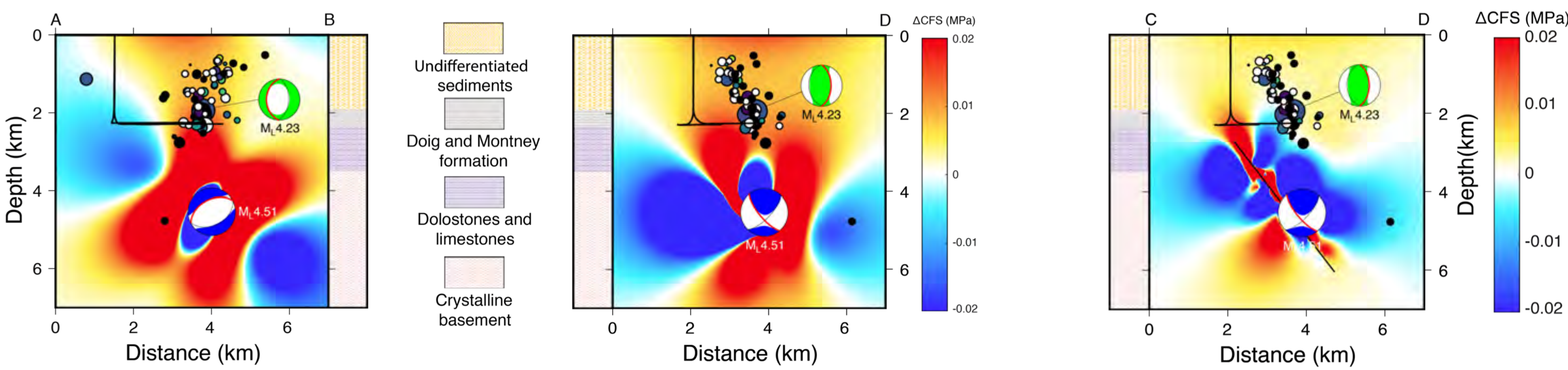
$$M_0 = \frac{16}{7}\Delta\sigma a^3$$

$a \sim 0.56$ km; $D \sim 10$ cm

Most aftershocks are within positive Coulomb stress change regime, can be explained by static stress transfer due to earthquake-earthquake interaction.







Conclusions

- Local, dense seismic arrays significantly improve detection threshold, highlighting strong spatial and temporal correlation between hydraulic fracturing and seismicity in the Kiskatinaw area.
- Stress drop values of induced earthquakes are 1-100 MPa, within the range typical for tectonic earthquakes. Well specific study reveals lower stress drops near the well, and higher at distance (pore pressure level), and strong Q variation (fracture density).
- The 2018/11/30 ML 4.5 sequence illustrates complex stress interactions between fluids, solid rock matrix and a nascent fracture network.
- Fault slip model suggests dependence on perturbation timing and amplitude, and fault initial stress level.

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