

An induced seismicity program for western Canada Past and current relevant induced-seismicity research



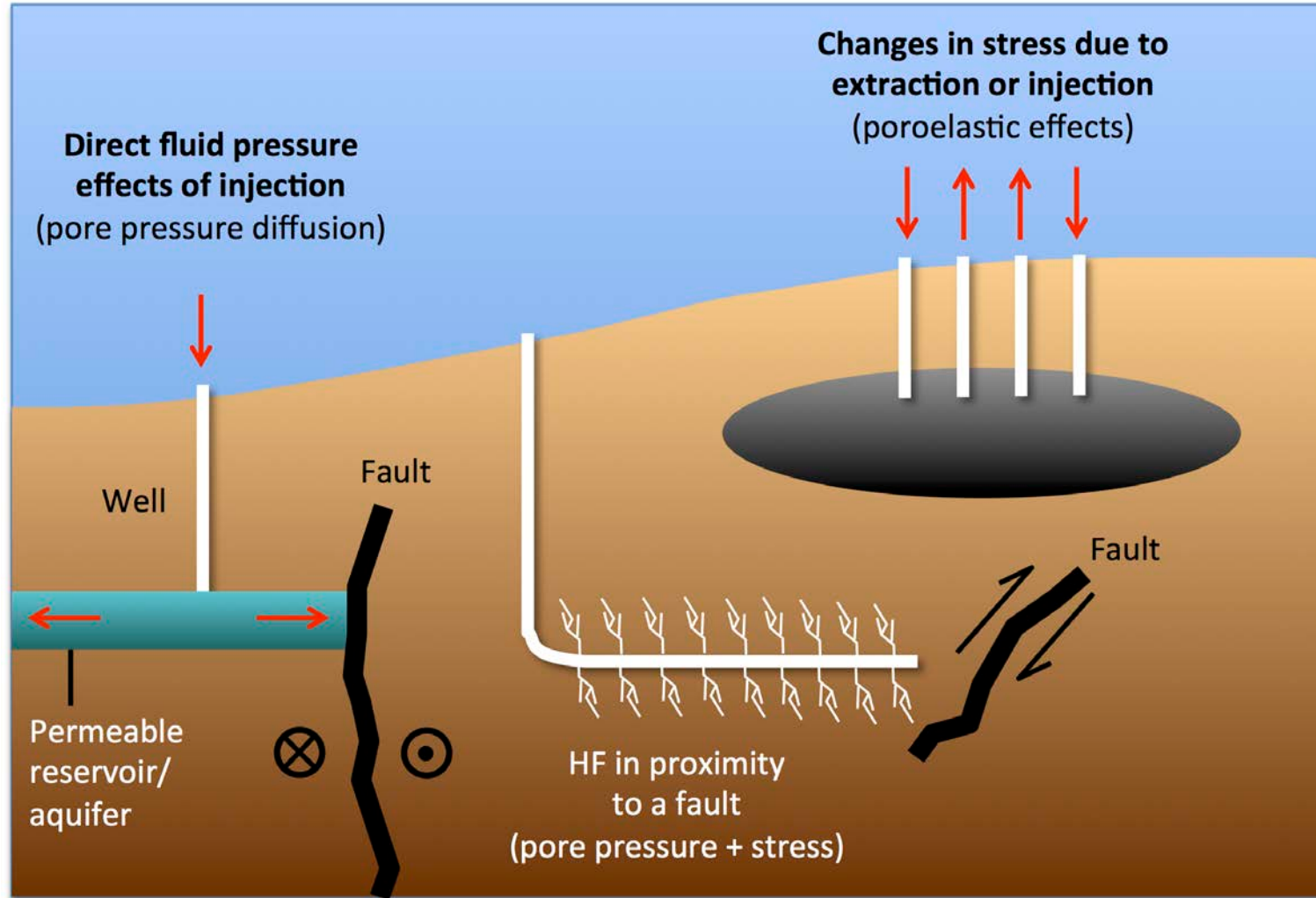
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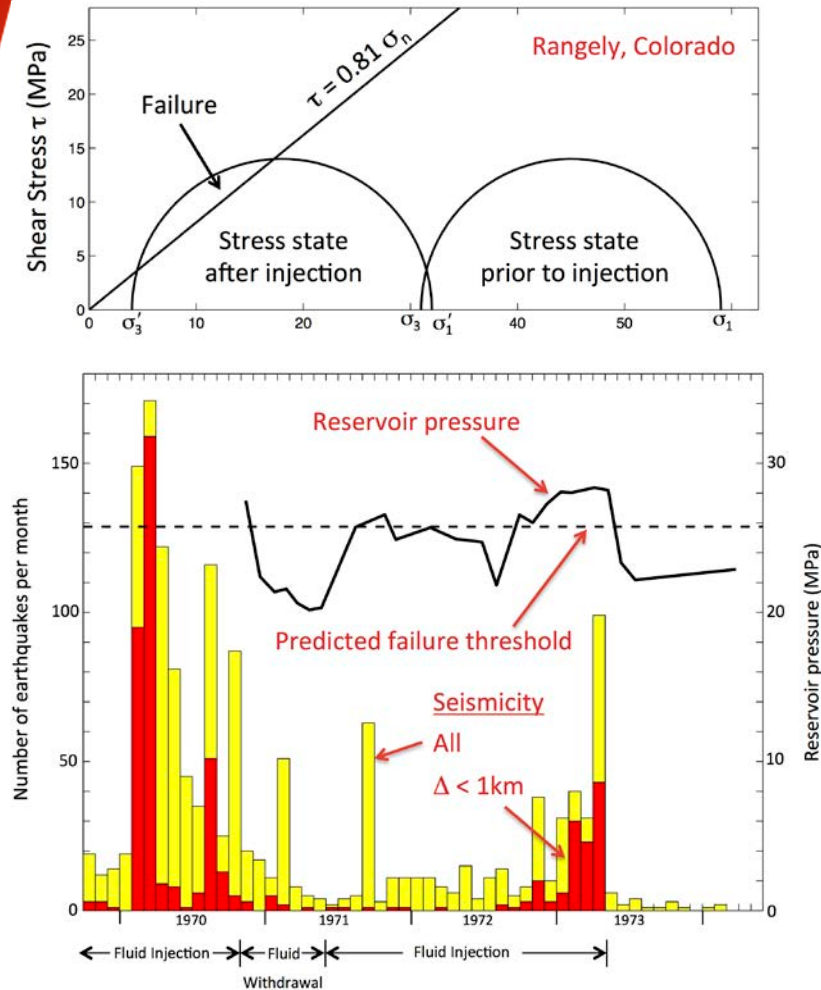
With contributions from and discussions
with: Xuewei Bao, Michael Brudzinski,
Gail Atkinson, Ryan Schultz, many
students and postdocs

Injection induced seismicity

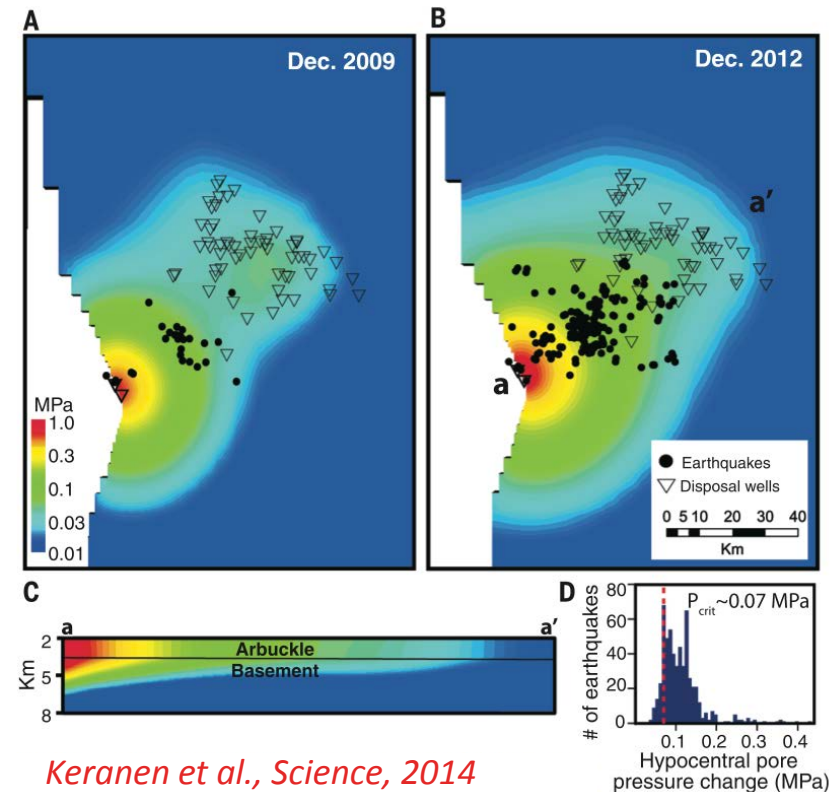


Eaton, 2016 (CETI Journal); modified from Ellsworth, Science, 2013

Role of pore pressure



Rayleigh et al., Science, 1976



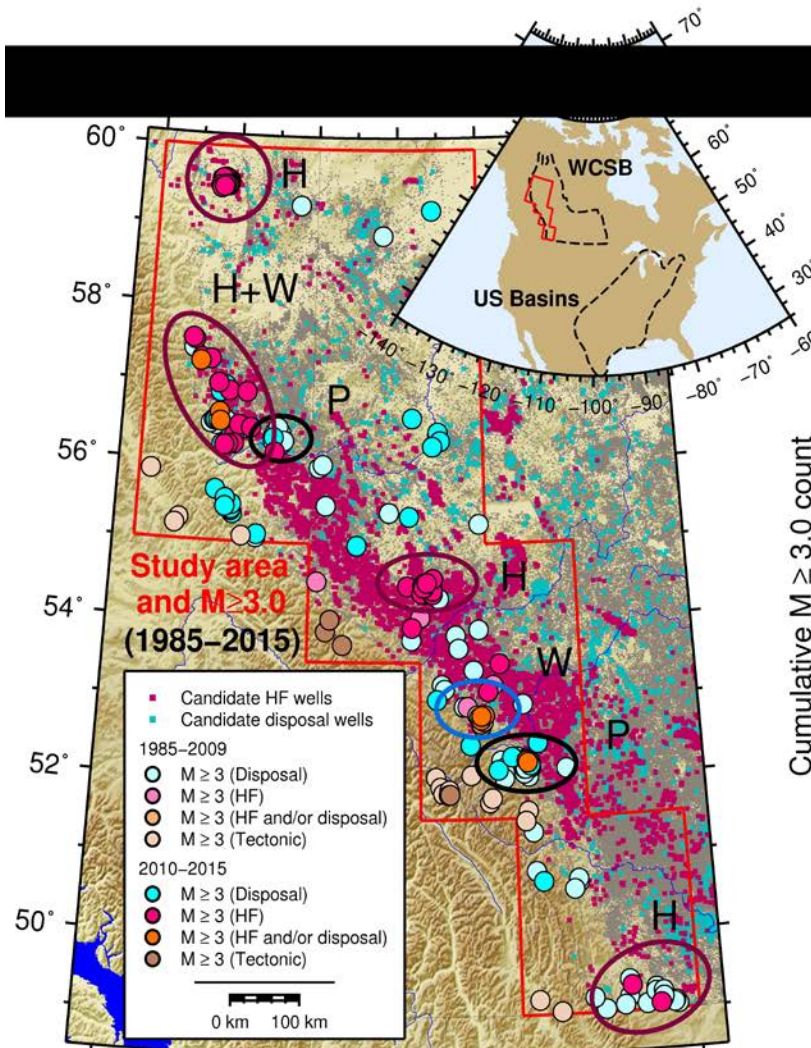
Keranen et al., Science, 2014

Rangely: model confirmation

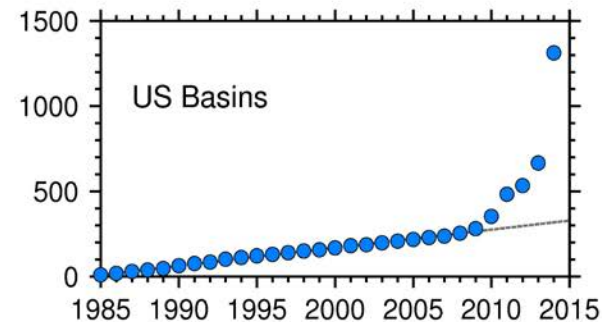
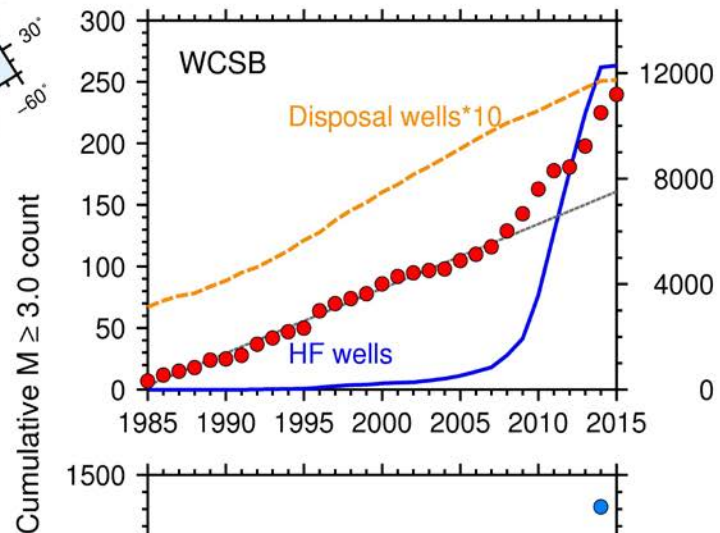
Oklahoma: relatively small pore-pressure increase ($\sim 0.07 \text{ MPa}$) implies critically stressed faults

Induced seismicity in western Canada

Induced seismicity from hydraulic fracturing (H) more prevalent than in the U.S.



Cumulative $M \geq 3.0$ and wells (1985–2015)



Cum. #HF wells – Cum #Disposal wells*10

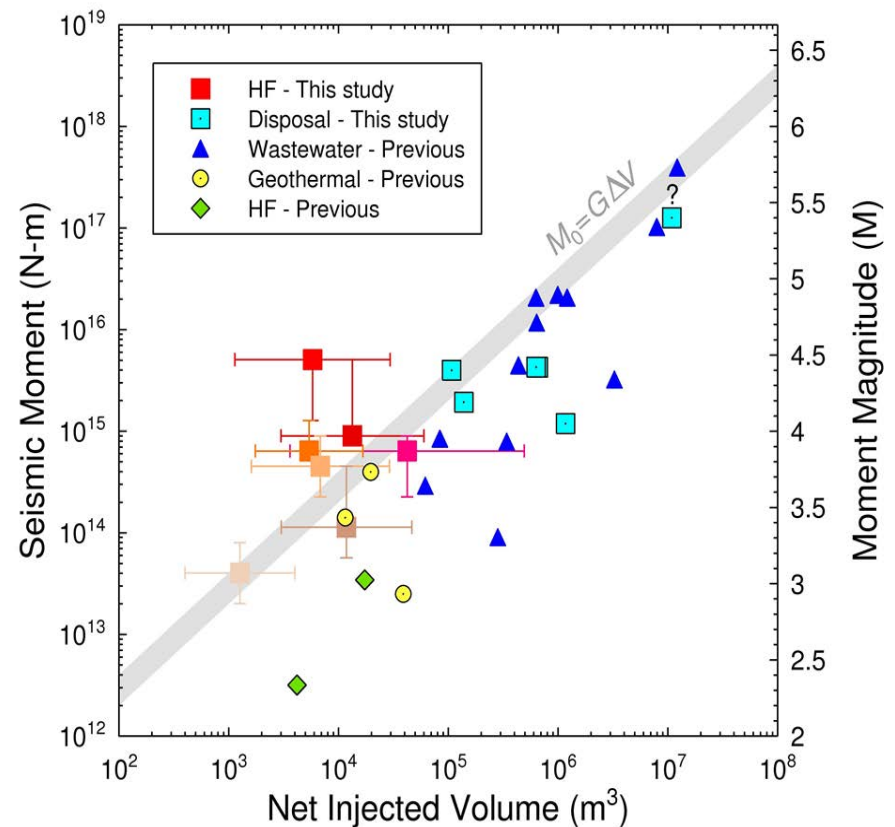
Induced seismicity in western Canada

- Estimated that 0.3% of HF wells are associated with $M > 3$ seismicity.
- In some cases, seismic moment exceeds bound from McGarr formula

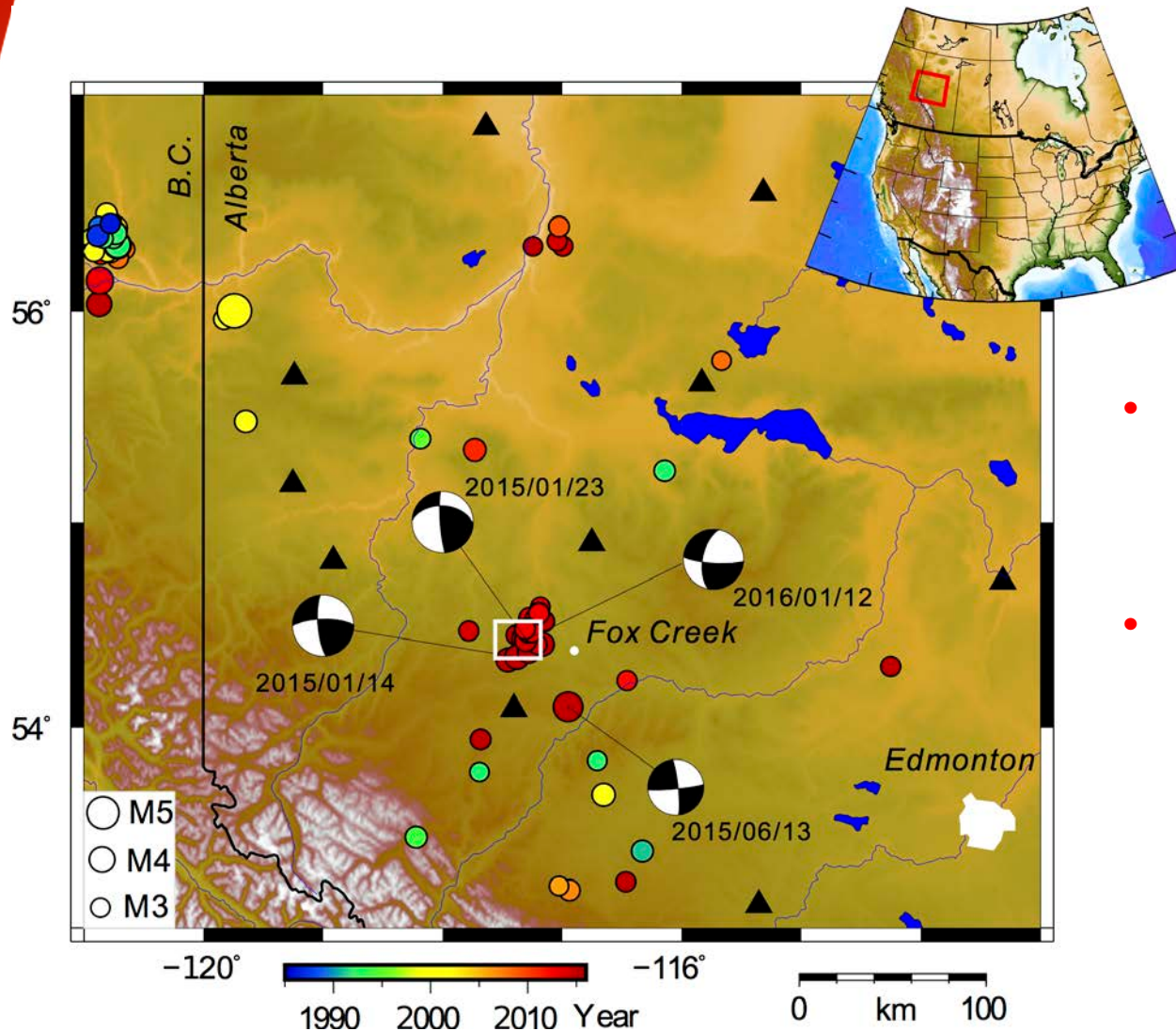
Table 1
Summary of Seismicity Associated with Wells
in the Western Canada Sedimentary Basin

	Disposal	HF	Tectonic $M \geq 3$
Number of candidate wells (1985–2015)	1236	12,289	—
Number of wells associated with $M \geq 3$	17	39	—
Association % for wells ($M \geq 3$)	~1%	~0.3%	—
Number of $M \geq 3$ (1985–2009)	126*	13*	14
Number of $M \geq 3$ (2010–2015)	33*	65*	7
Association % for $M \geq 3$ (2010–2015)	31%	62%	7%

*These totals each include 18 events for which both disposal and hydraulic fracture (HF) wells could be associated, 8 of which occurred from 2010 to 2015; in assessing % association rates, each such event has been counted as ½. See [Data and Resources](#) for lists of associated wells and events.



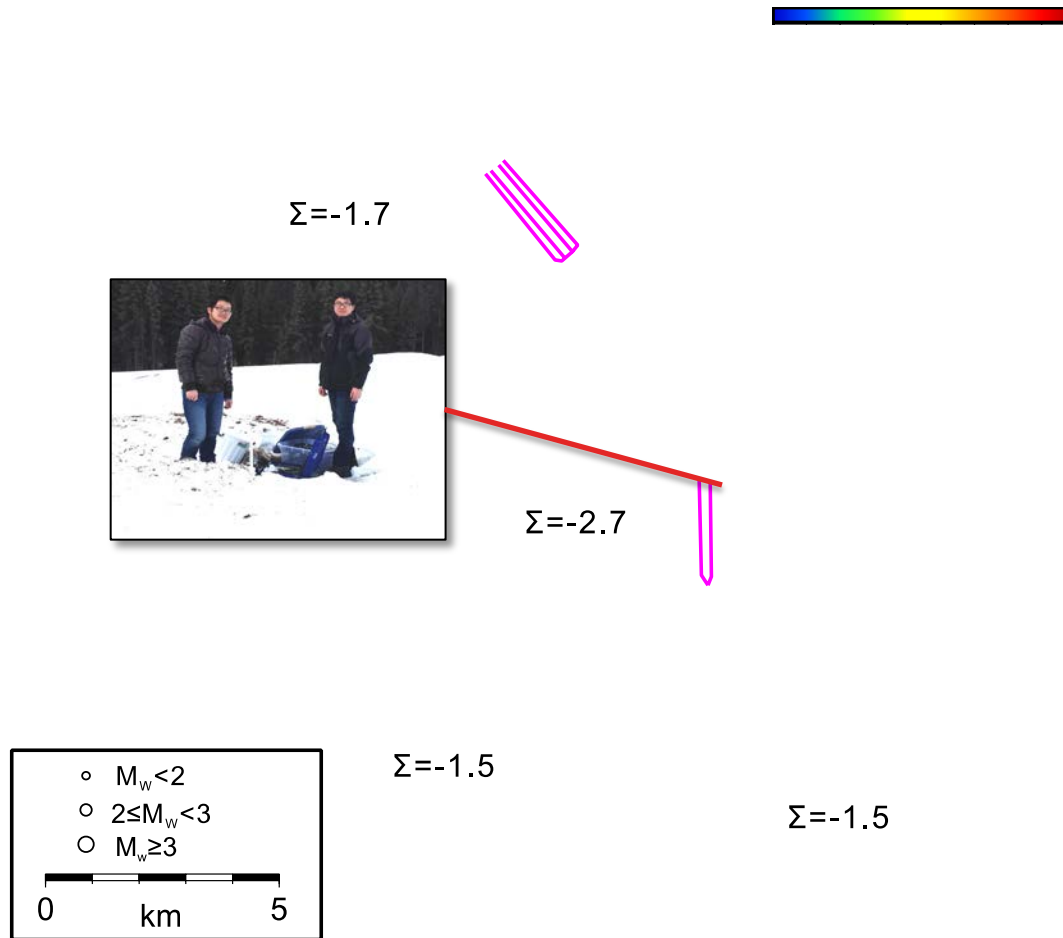
Case Study: Fox Creek Region, AB



- Fox Creek area was seismically quiescent until 2013
- Subsequently, induced seismicity has been linked to hydraulic fracturing of the Duvernay shale

Case Study: Fox Creek Region, AB

Latitude

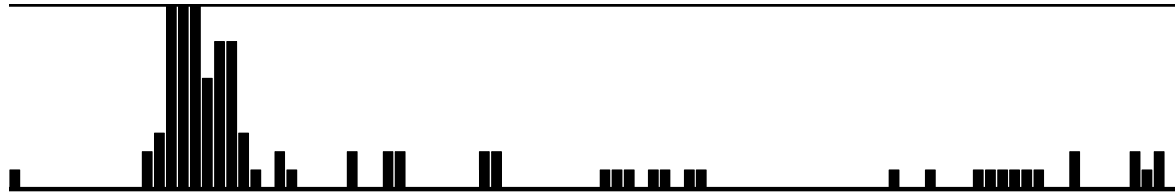


- Seismicity from December 2014 to March 2015
- Methods: matched filtering, double-difference event locations
- Strongly clustered near treatment wells at 6 pads

Bao and Eaton, Science, 2016

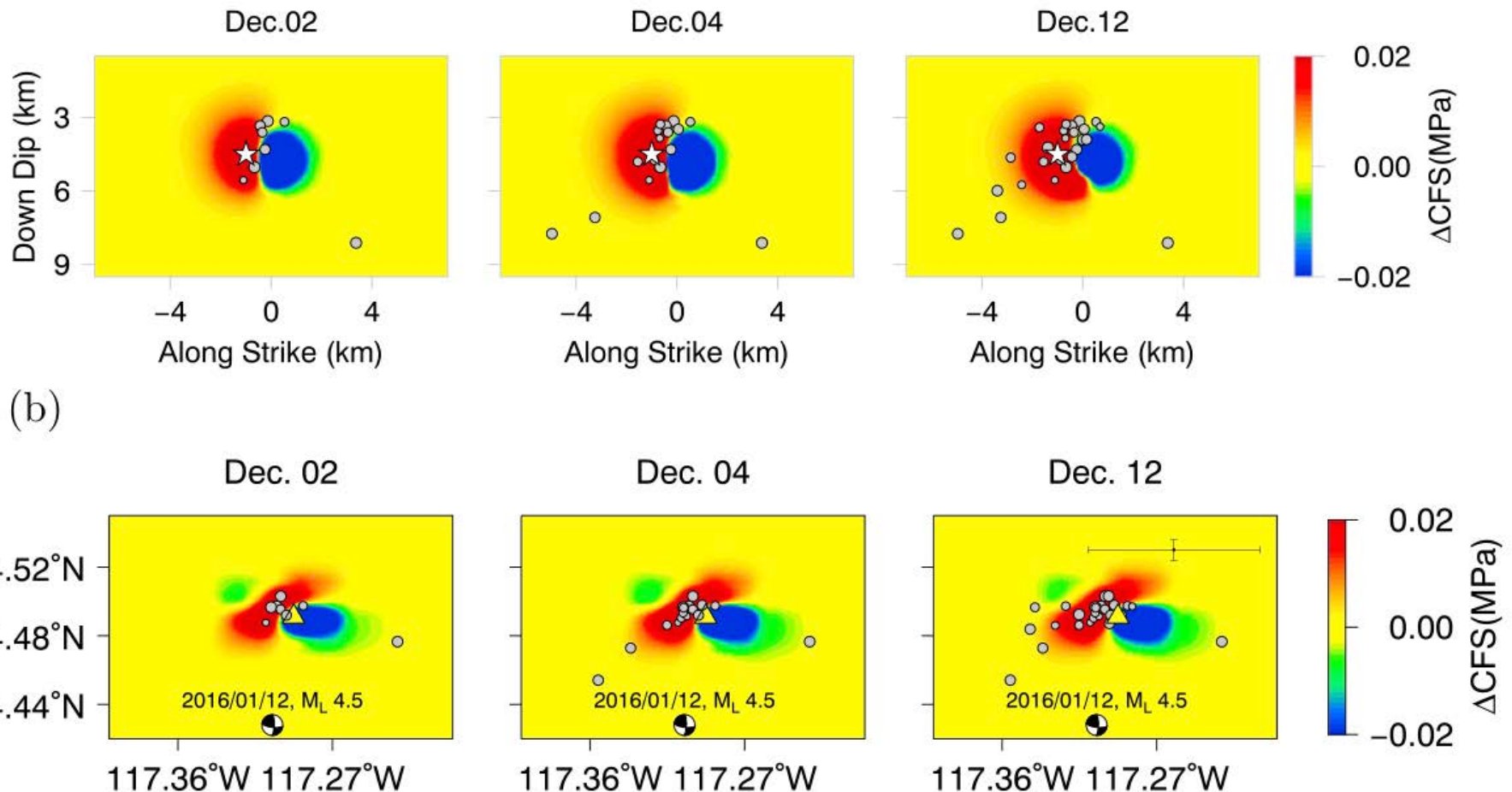
Seismicity vs. Injection Data

- Largest event during flowback – but unusually low fluid recovery
- Episodic seismicity persists throughout W2015 (S1, S2, S3) -- but lacking typical aftershock sequence
- Maximum magnitude (M_w 3.9) at upper limit of bound using McGarr formula



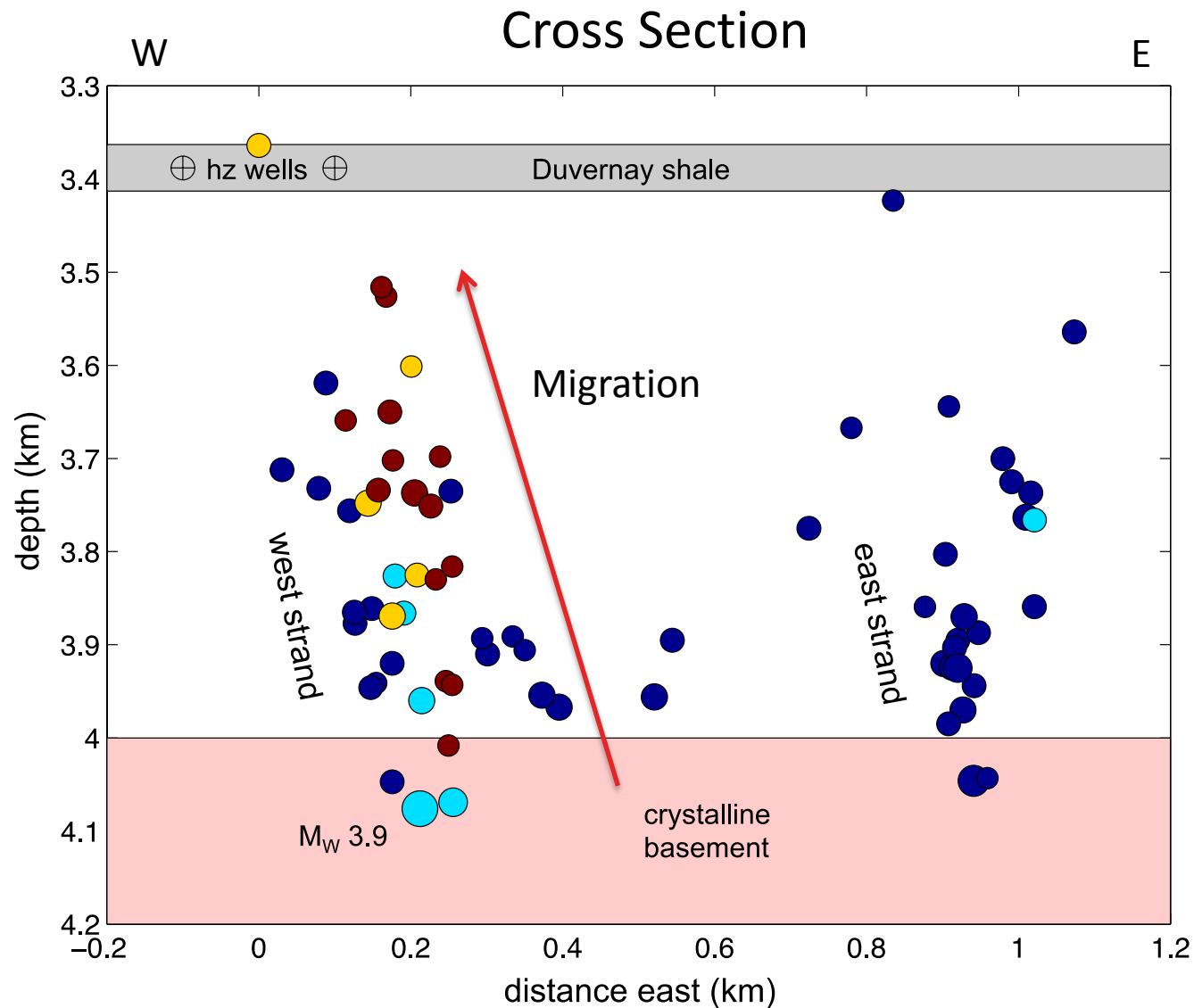
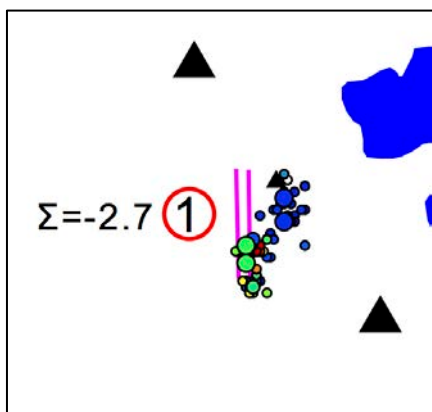
Elastic response of solid matrix

Linear poroelastic simulations indicate that “elastic response of the solid matrix, instead of fluid diffusion, is more likely the dominant factor for the induced earthquakes shortly after fluid injection.”

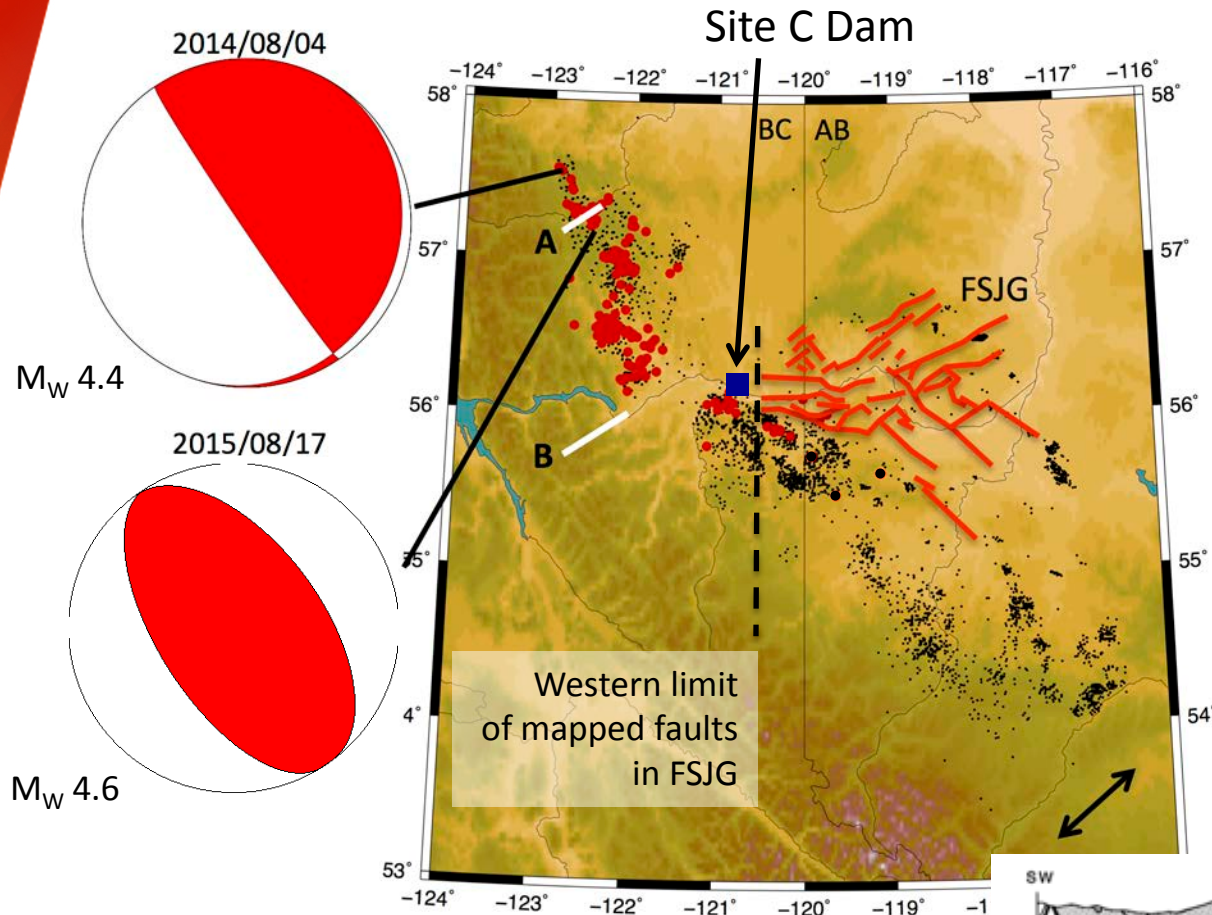


Multiple strands – varying response

East: transient
West: persistent



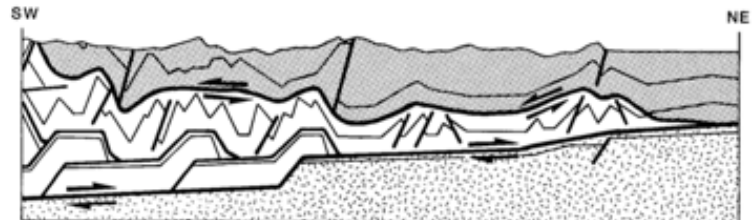
Seismicity in the BC Montney Trend



Late Carboniferous normal faults, Fort St. John Graben system (FSJG)

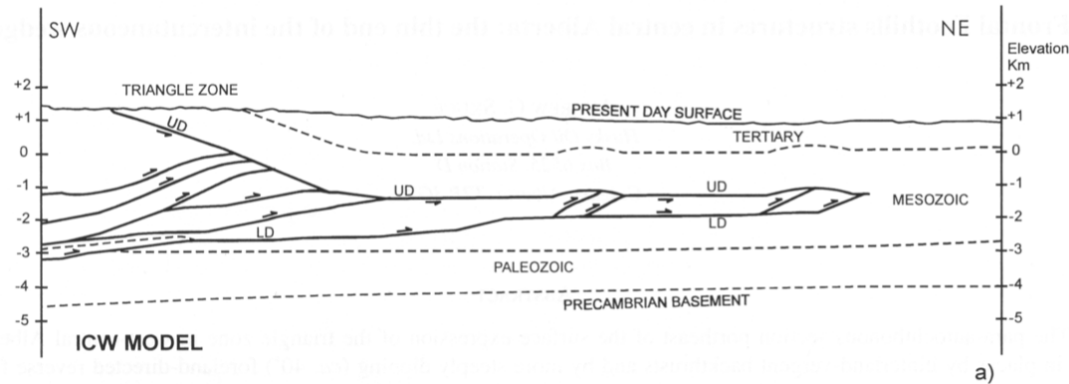
Largest events have a low-angle thrust or reverse mechanism (Zhang et al., JGR, 2016; Mahani et al., submitted)

Intercutaneous wedge? (Skuce, 1996)



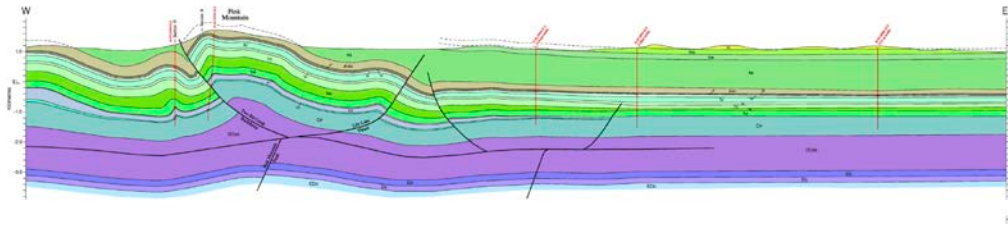
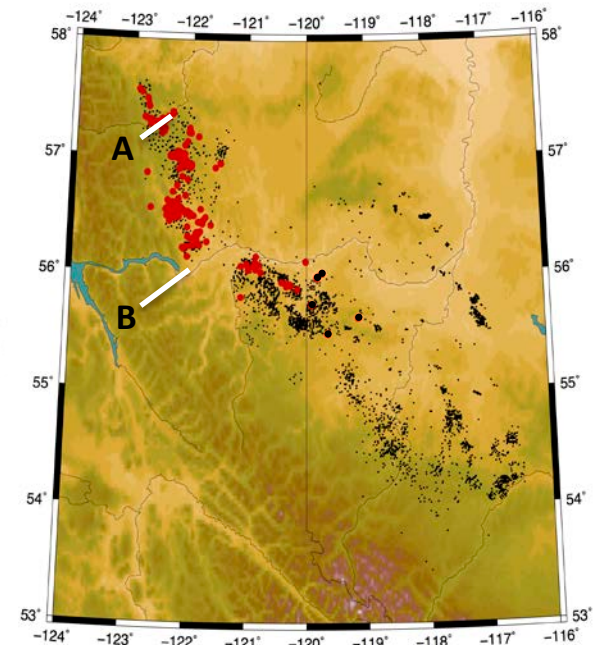
Profile B, McMechan 1985

Seismicity in the BC Montney Trend

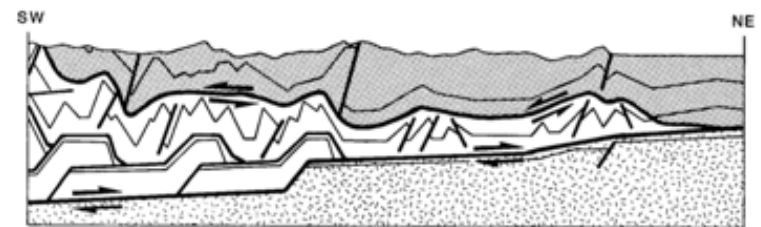


Intercutaneous wedge (ICW): “The body of rock situated between the hinterland verging upper detachment (UD) and the foreland-verging lower detachment (LD)”.

Skuce, 1996



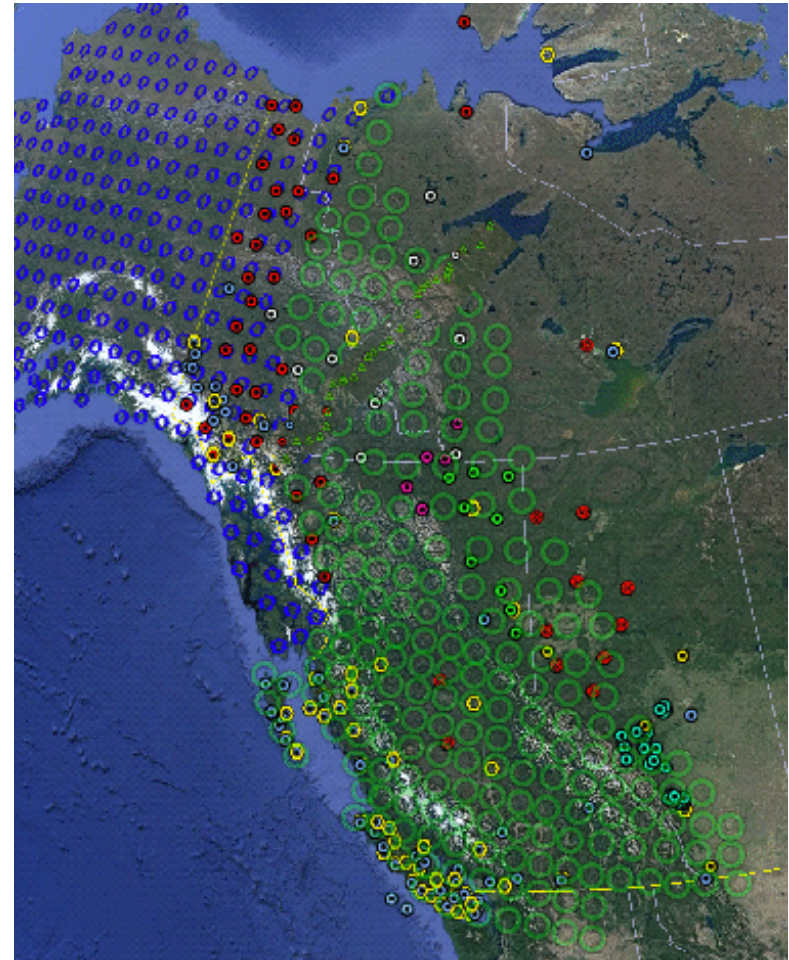
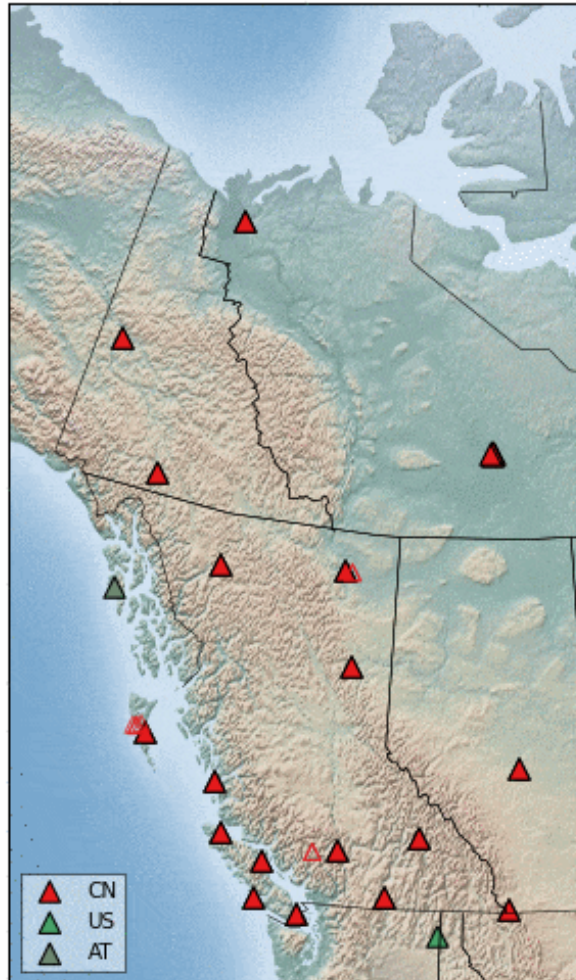
Profile A, Hinds and Cecile, 2003



Profile B, McMechan 1985

CCArray and past/current stations

2000.01



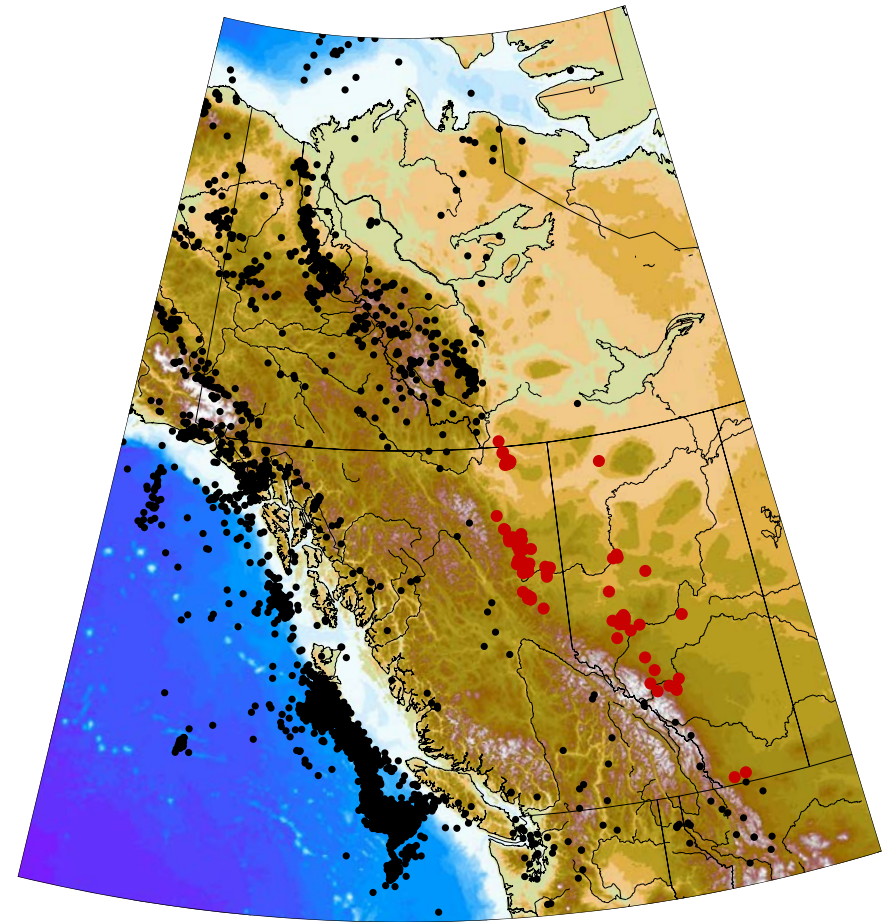
Courtesy P. Audet

M > 3 seismicity since 2008

Potential induced events in red

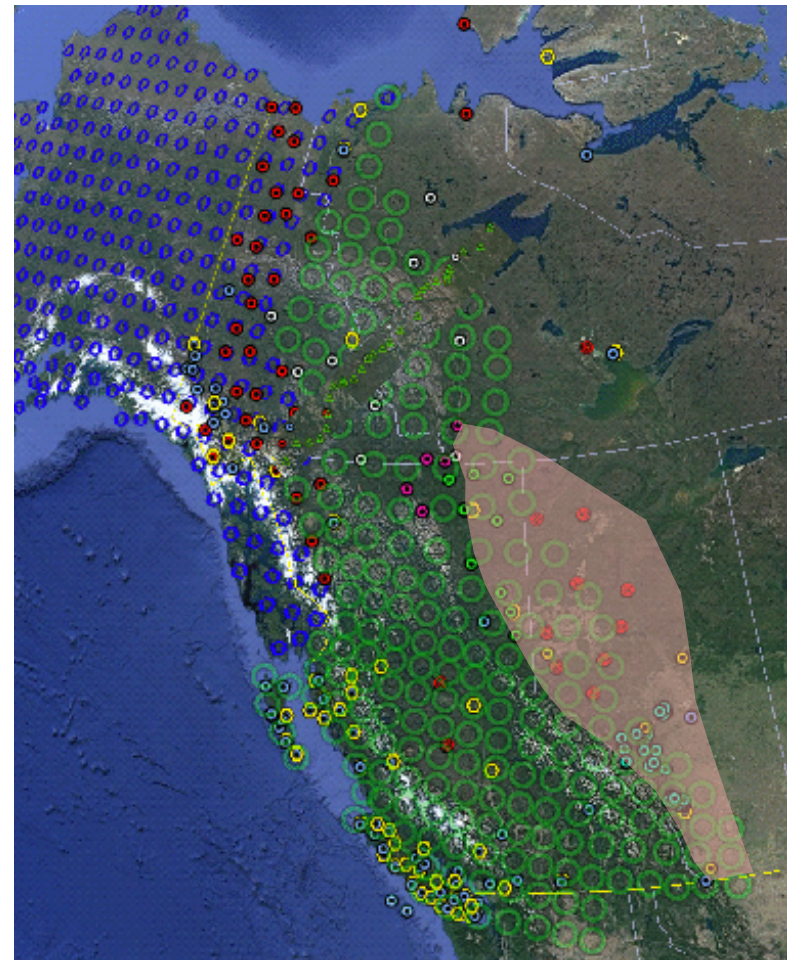


Courtesy P. Audet



Source: Earthquakes Canada

Region of interest for induced seismicity



Courtesy P. Audet

Considerations for induced-seismicity monitoring

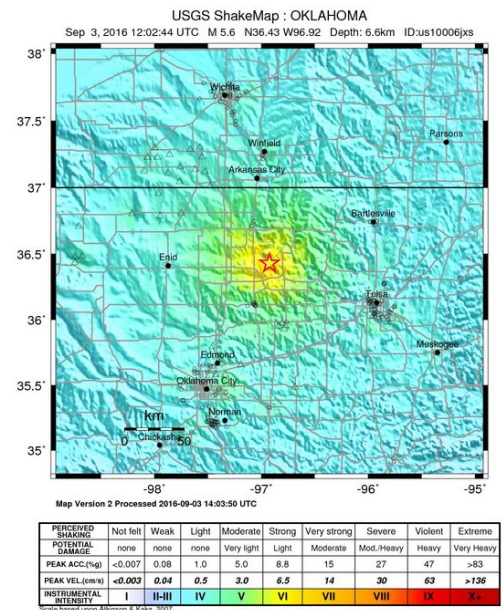
1. Utilize existing broadband seismograph stations (possibly by enhancing existing equipment or extending the time period)
2. Monitoring may require a longer operational time window than is needed for TA-style deployment (→ fist in, last out?)
3. Desirable to achieve uniform magnitude of completeness ($M \sim 2?$), publicly accessible ground motion data and capability to produce Shakemaps



Shakemap

M_W 5.8, Pawnee OK
2016/09/03

Source: USGS



Courtesy P. Audet

1. Western Canada has experienced a sharp increase in rate injection-induced seismicity, comparable to U.S. Midwest but with greater prevalence of HF induced seismicity
2. Localized areas of elevated IS risk generally occur near (< 200 km) the deformation front, suggesting a causal link (stress? Intercutaneous wedge?)
3. Fault activation may be triggered by pore pressure or stress. Pressurized faults exhibit persistent seismicity
4. Opportunity to combine fundamental research with an urgent societal issue of high economic consequence