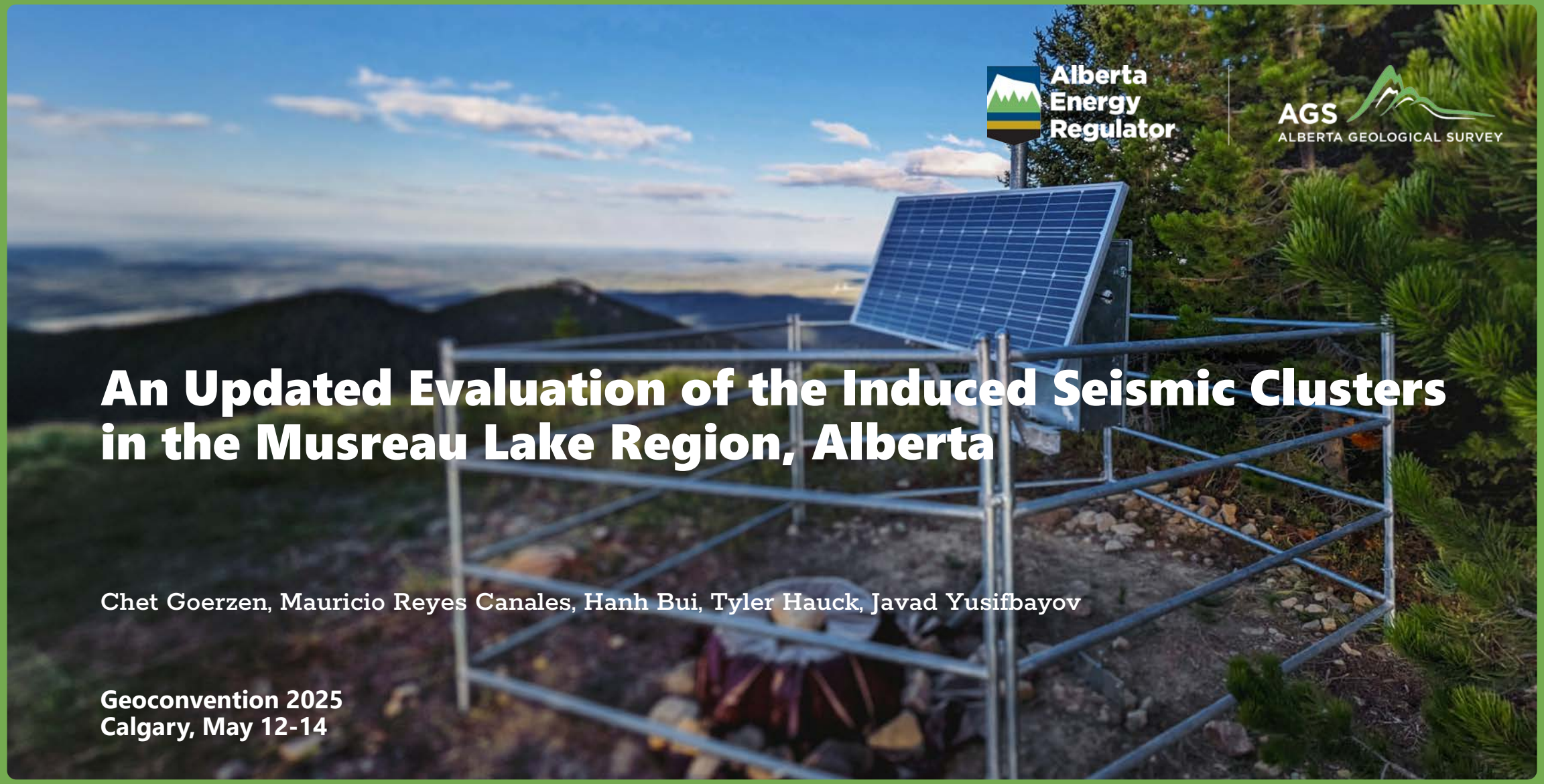

An Updated Evaluation of the Induced Seismic Clusters in the Musreau Lake Region, Alberta

Chet Goerzen, Mauricio Reyes Canales, Hanh Bui, Tyler Hauck, Javad Yusifbayov

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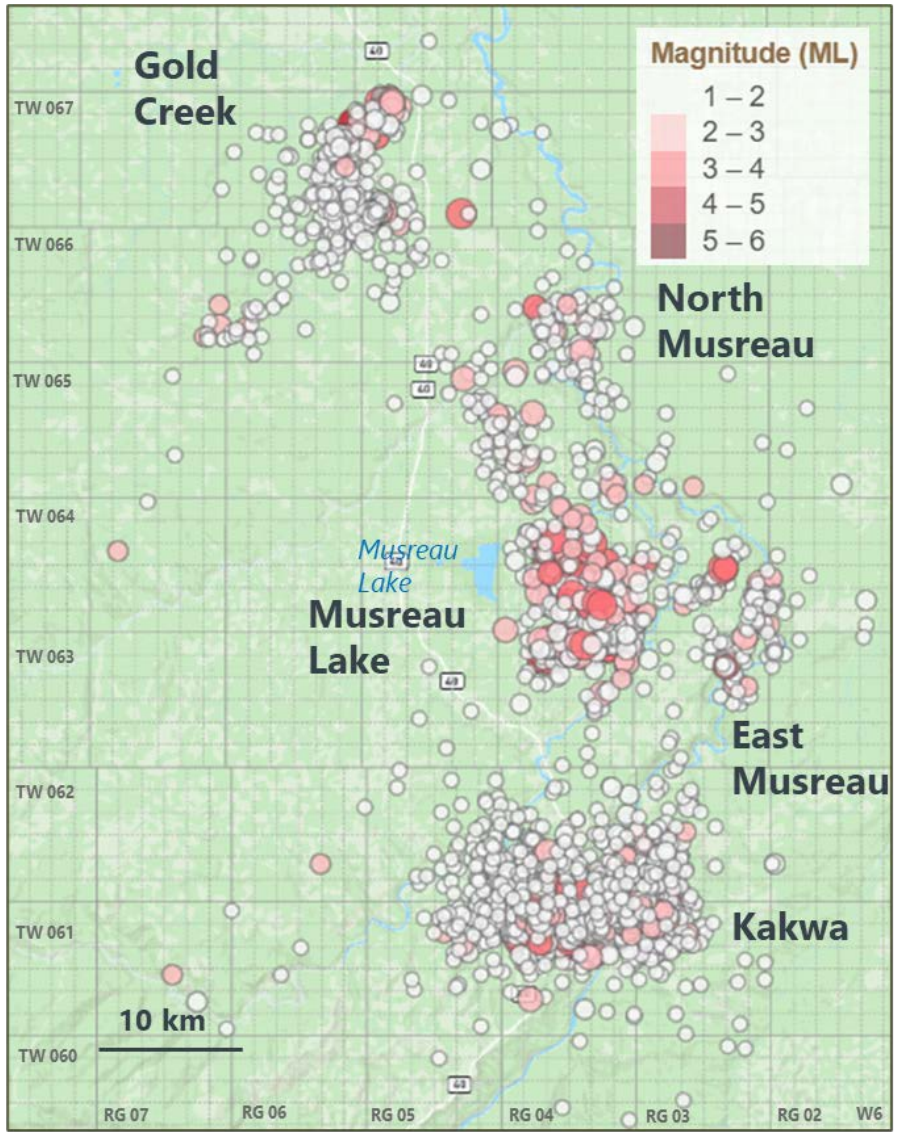
Introduction

- Multiple cases of water-disposal induced seismicity have emerged in northwestern Alberta: Musreau Lake (Central, East and North), Gold Creek, and Kakwa.
- Disposal fluids come from nearby Montney Fm. production.
- Two of these cases are primarily related to disposal into the Leduc Fm. (Gold Creek and Kakwa), and another case is related to disposal into the Winterburn Gp. (Musreau Lake).
- The largest event detected to date (M=5.08) was located in the Kakwa cluster.
- No damage has been registered. However, widespread public nuisance has been caused by the largest events.



Induced seismic clusters south of the Grande Prairie region

Geological background

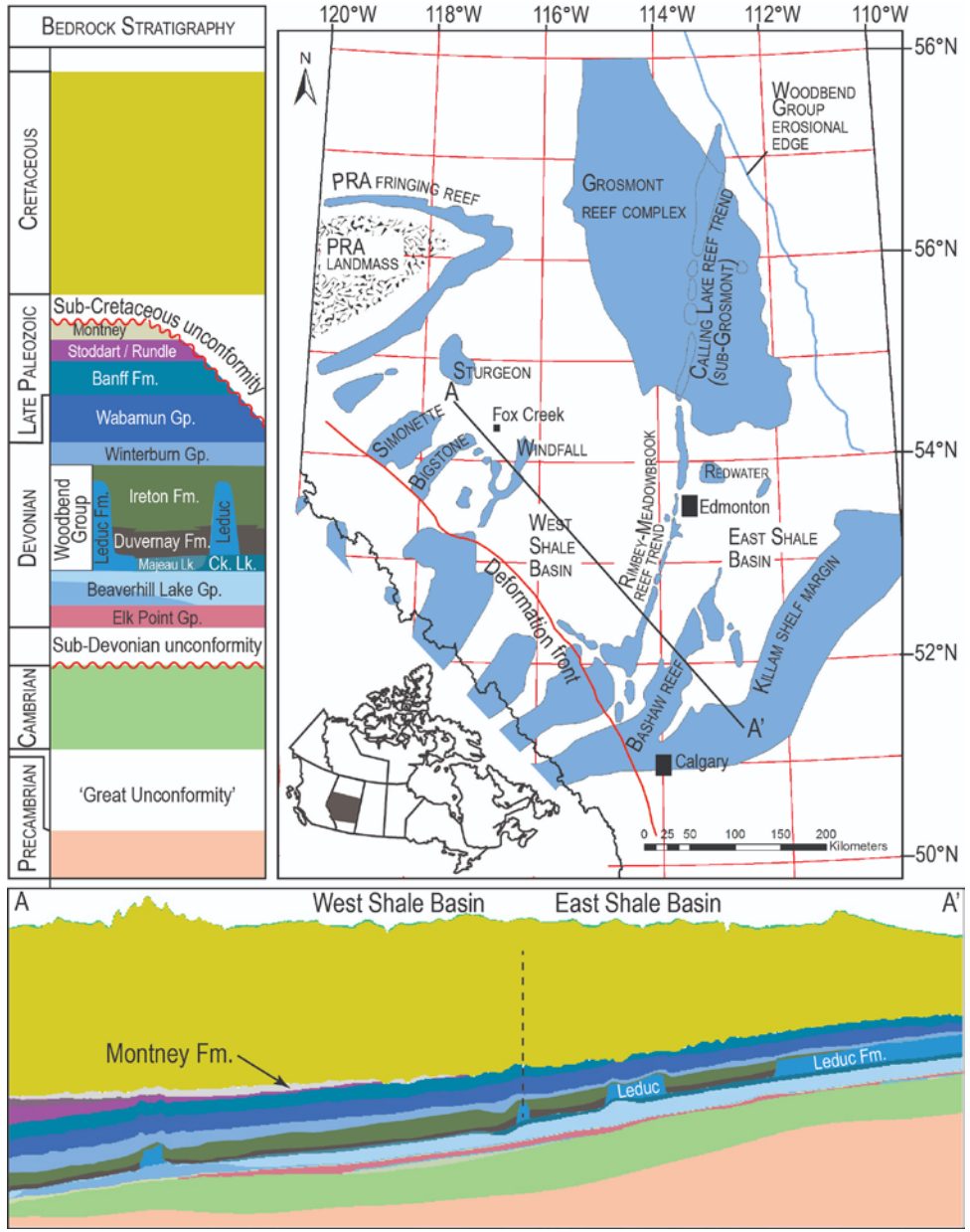
Induced seismicity has been associated with disposal in the Late Devonian Woodbend & Winterburn groups.

The Woodbend target is the Leduc Formation:

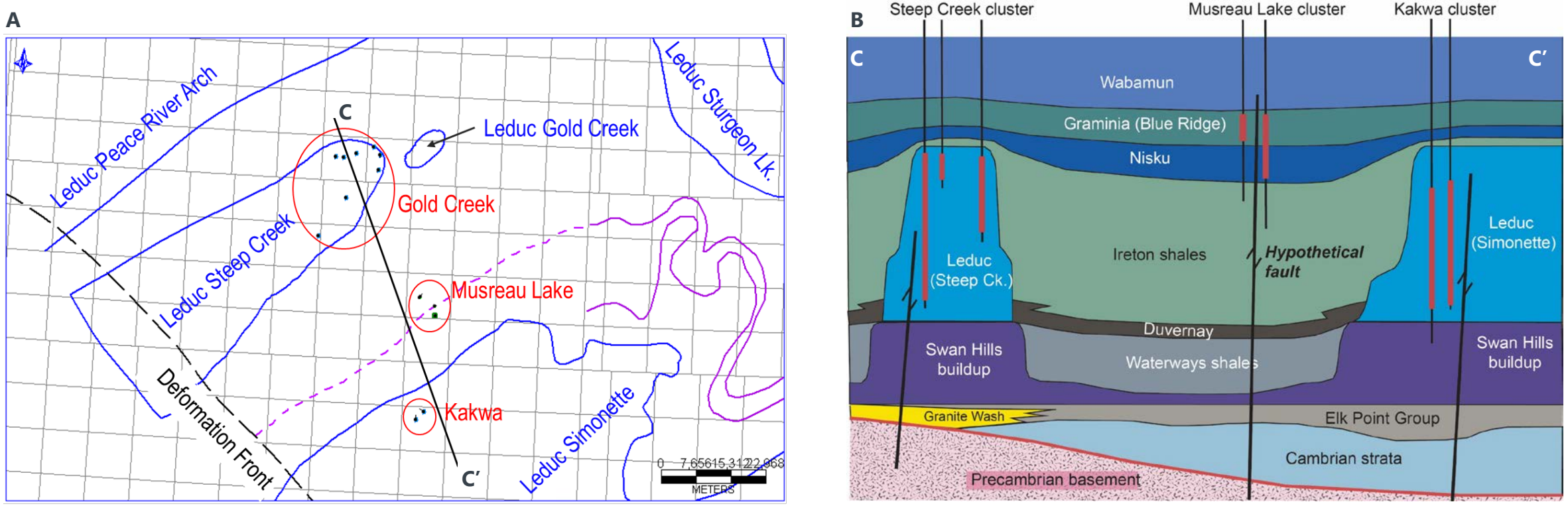
- Thick, shallow-water carbonate buildup (reef) encased in shales.
- We know very little about the Leduc Reefs in the study area due to a lack of well and core control (no hydrocarbon pools).

The Winterburn target is the Nisku and Graminia formations:

- Broad, shallow-water carbonate platform with evaporites (anhydrite).
- Recrystallized dolomite with white sparry hydrothermal dolomite in vugs and fractures.
- Por/perm highly variable, controlled by the distribution of hydrothermal dolomite.



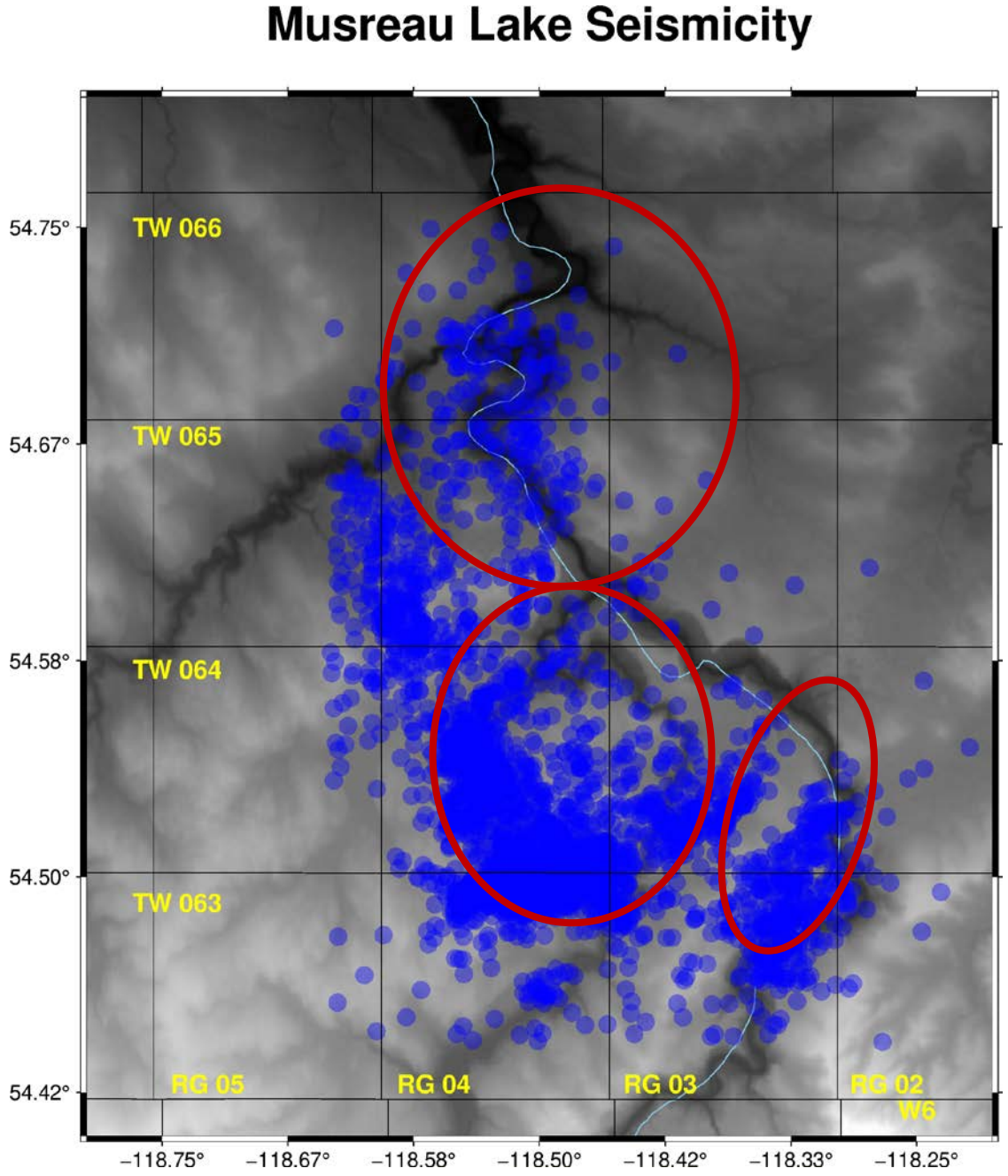
Geological background



Map view (A) of the Leduc Formation reef edge and Swan Hills build-ups in the region south of Grande Prairie. Figure (B) shows a geological schematic from a northwest–southeast cross-section C-C′. Notice the seismogenic disposal activities in the Leduc reefs and the Winterburn Gp. (red bars on vertical black lines representing the wells) and the hypothetical faults extending to the basement.

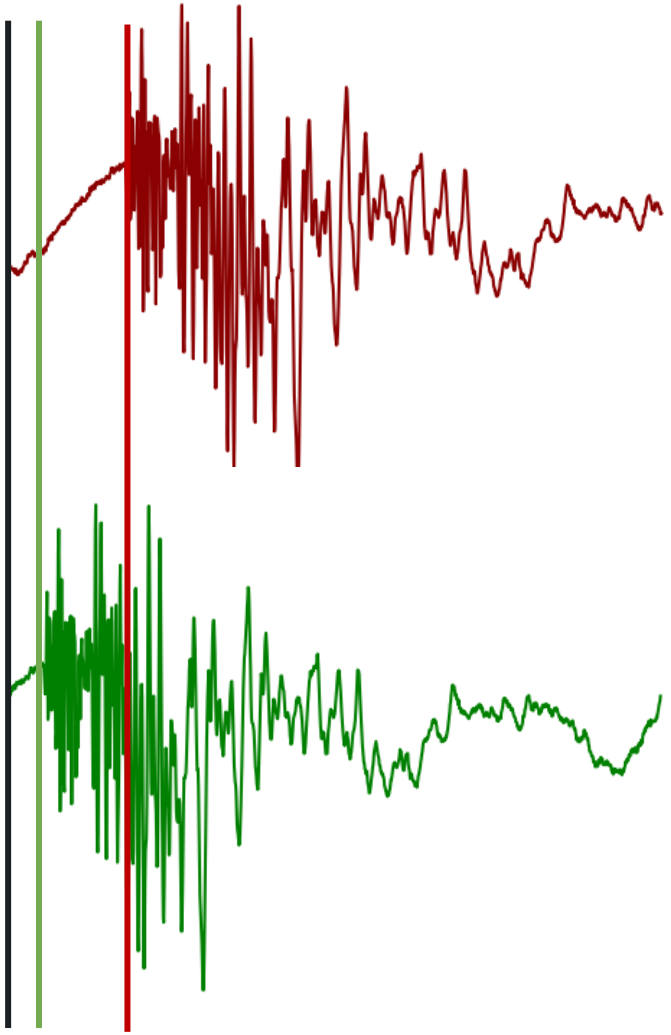
Musreau Lake earthquake sequence

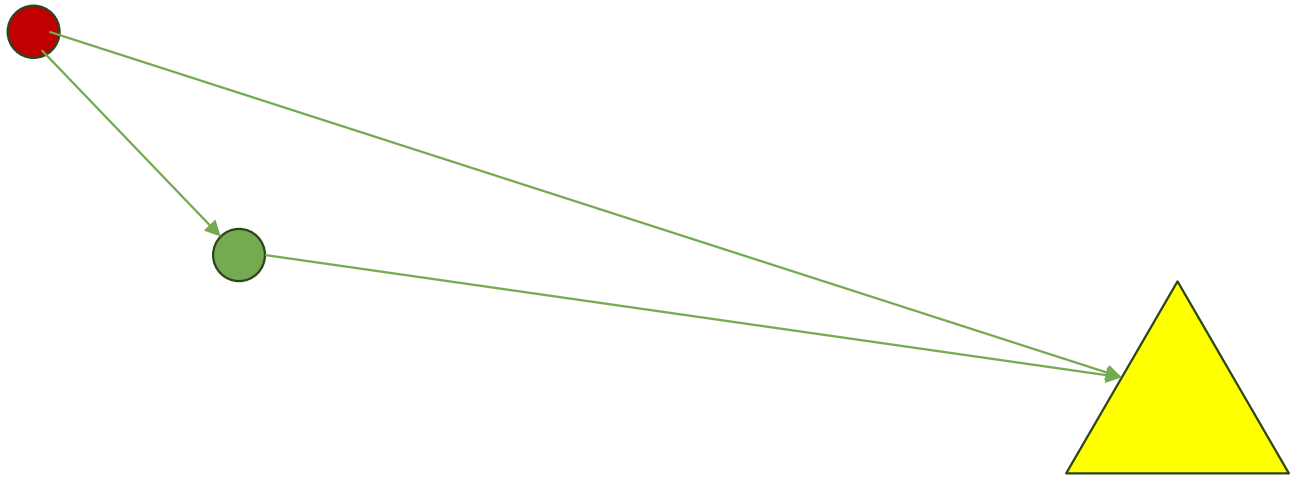
- 3160 events have been detected in the Musreau Lake region from December 2019 to March 2025
- Event magnitudes ranged between M -0.78 to M 3.94
- Three main clusters are observed: Central, East and North.
- Only events above M 1 are published to the AER public dashboard



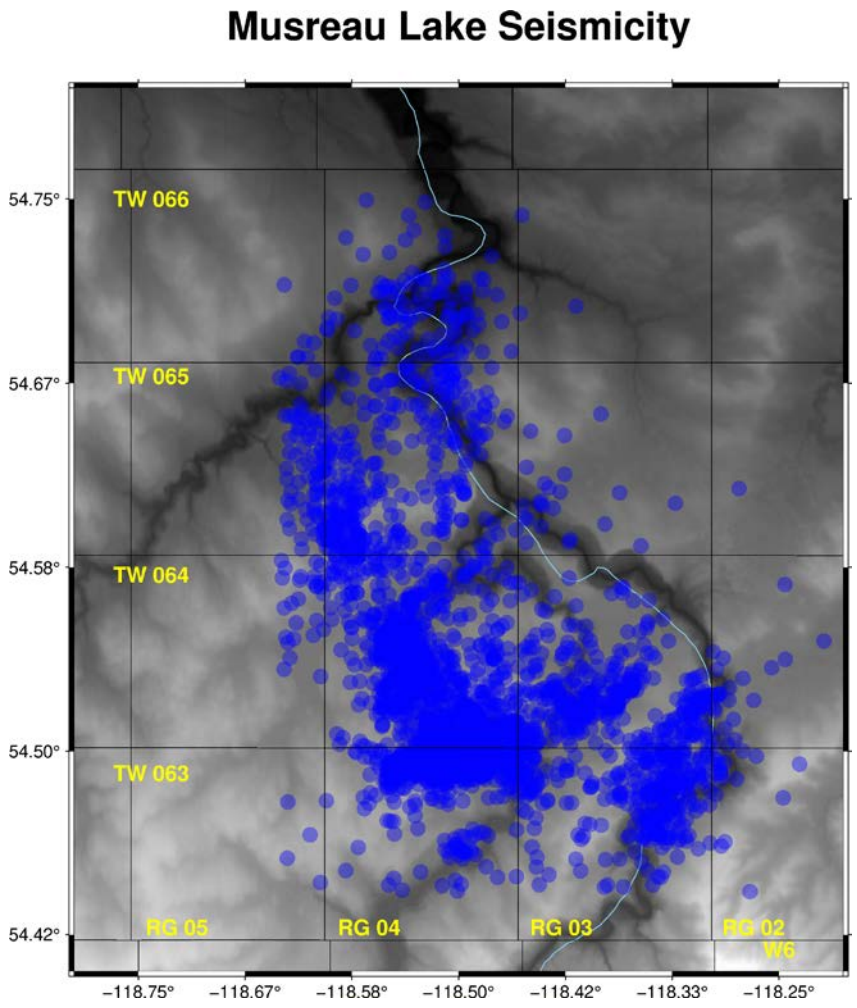
HypoDD

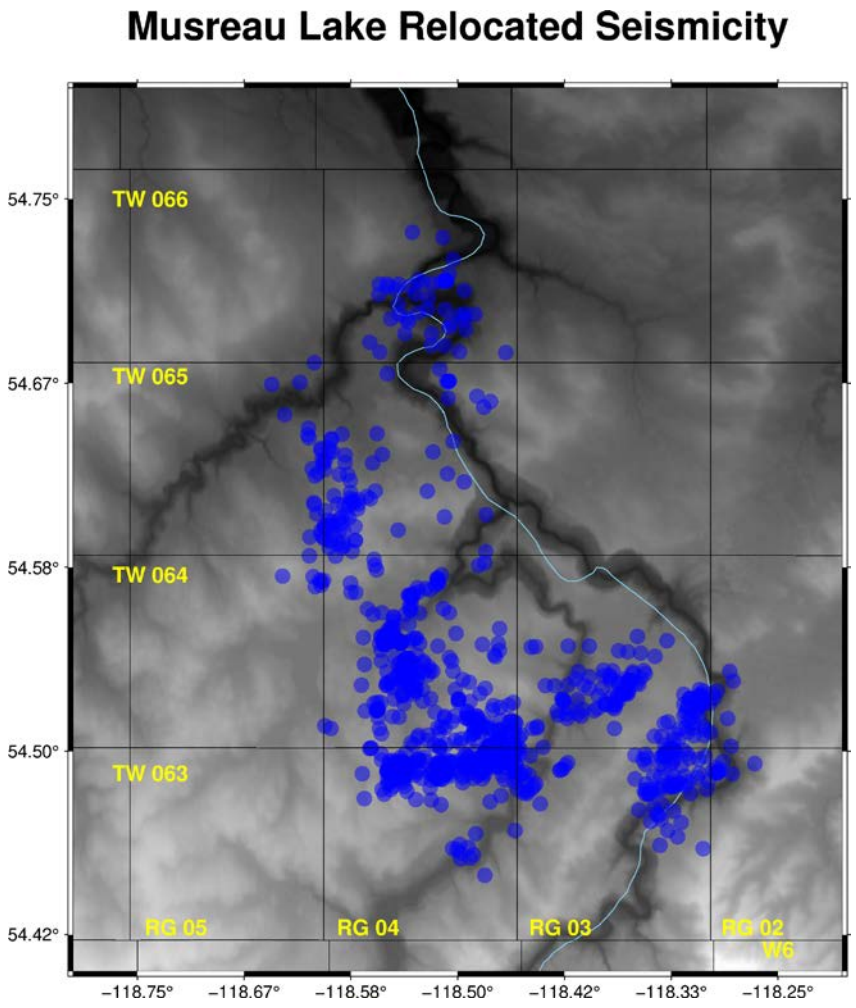
- Travel time differences are used to calculate relative differences in earthquake locations
- Cross-correlation measurements may be used to increase precision





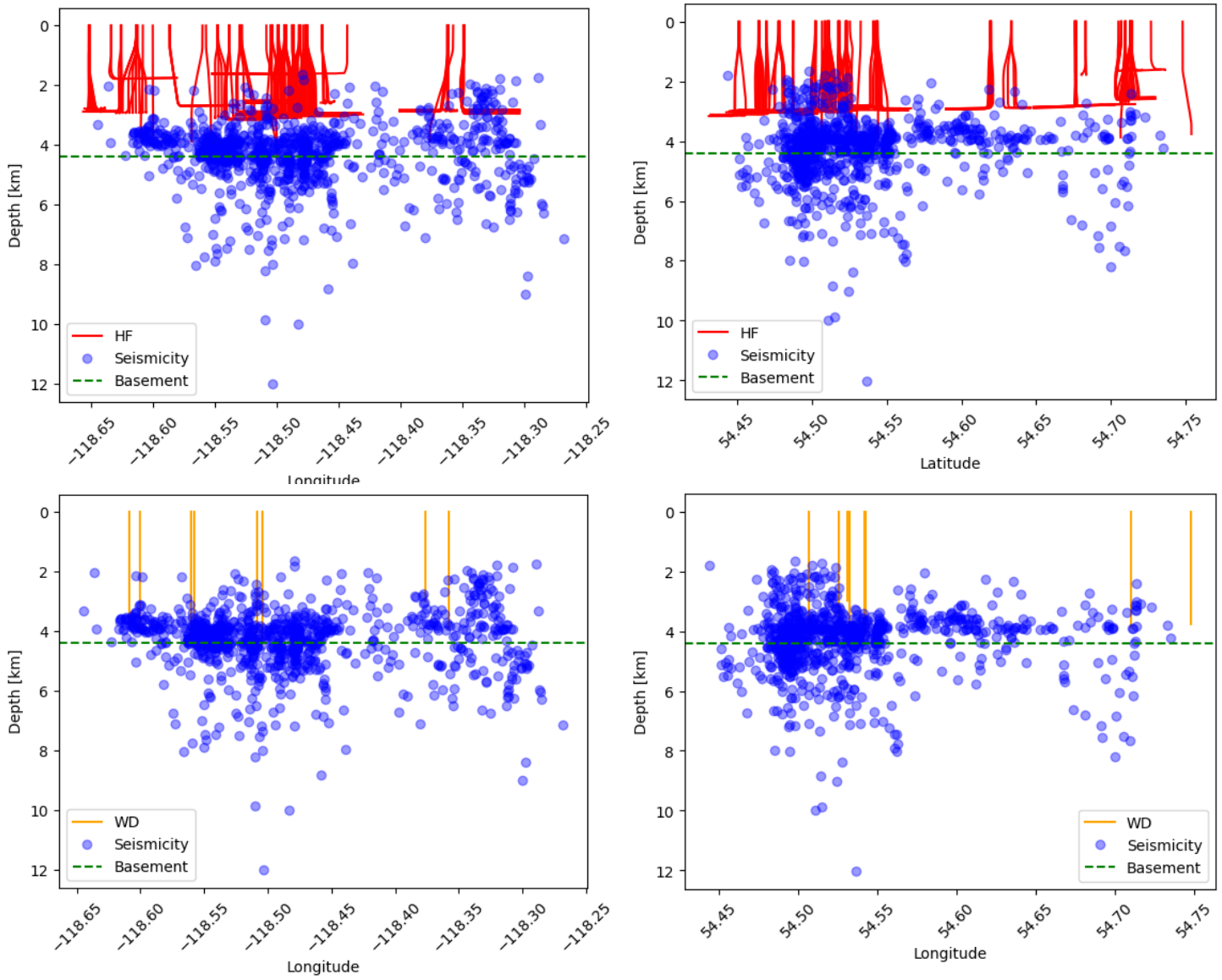
Relocated Results

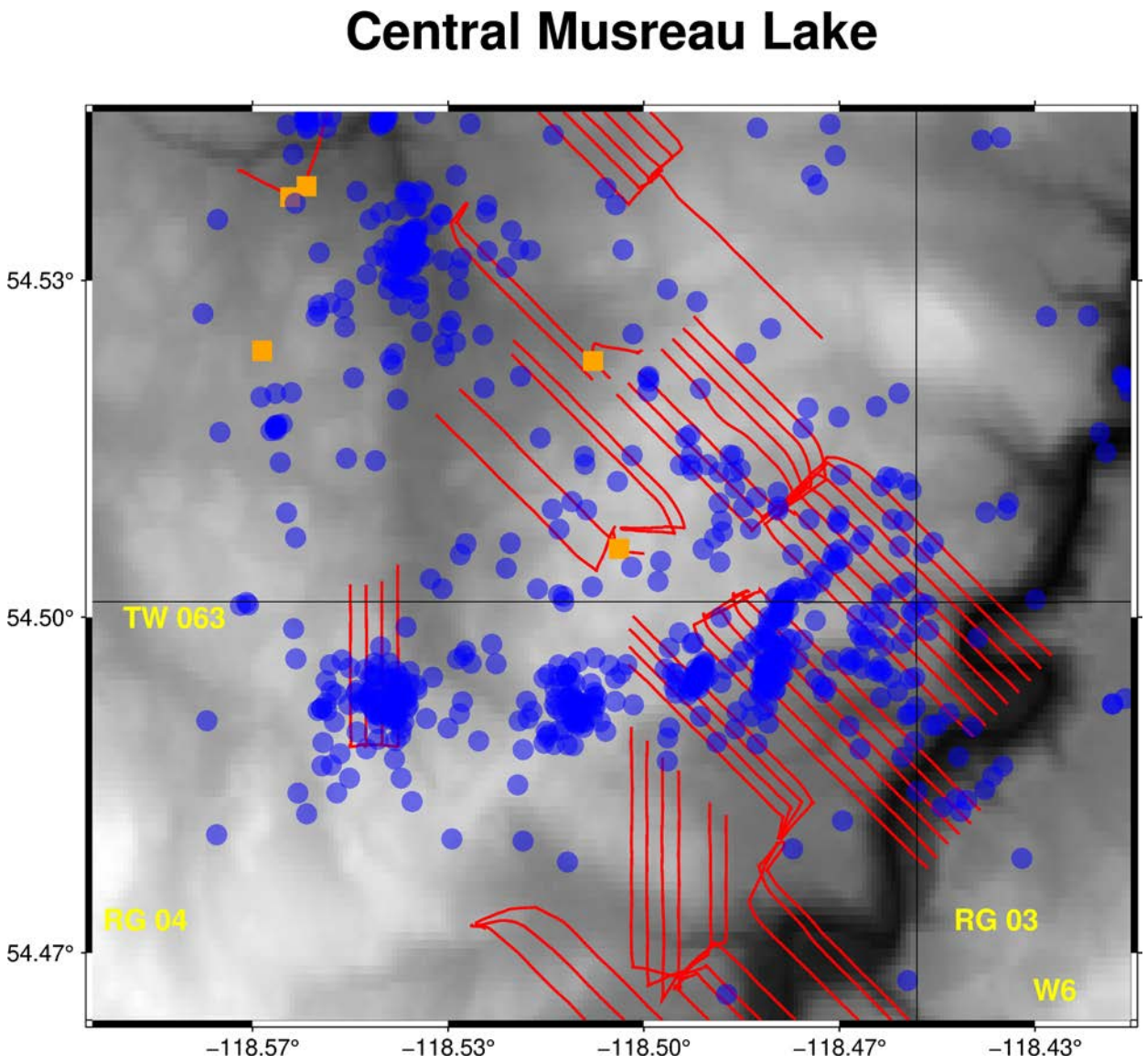




Depth View of Seismicity

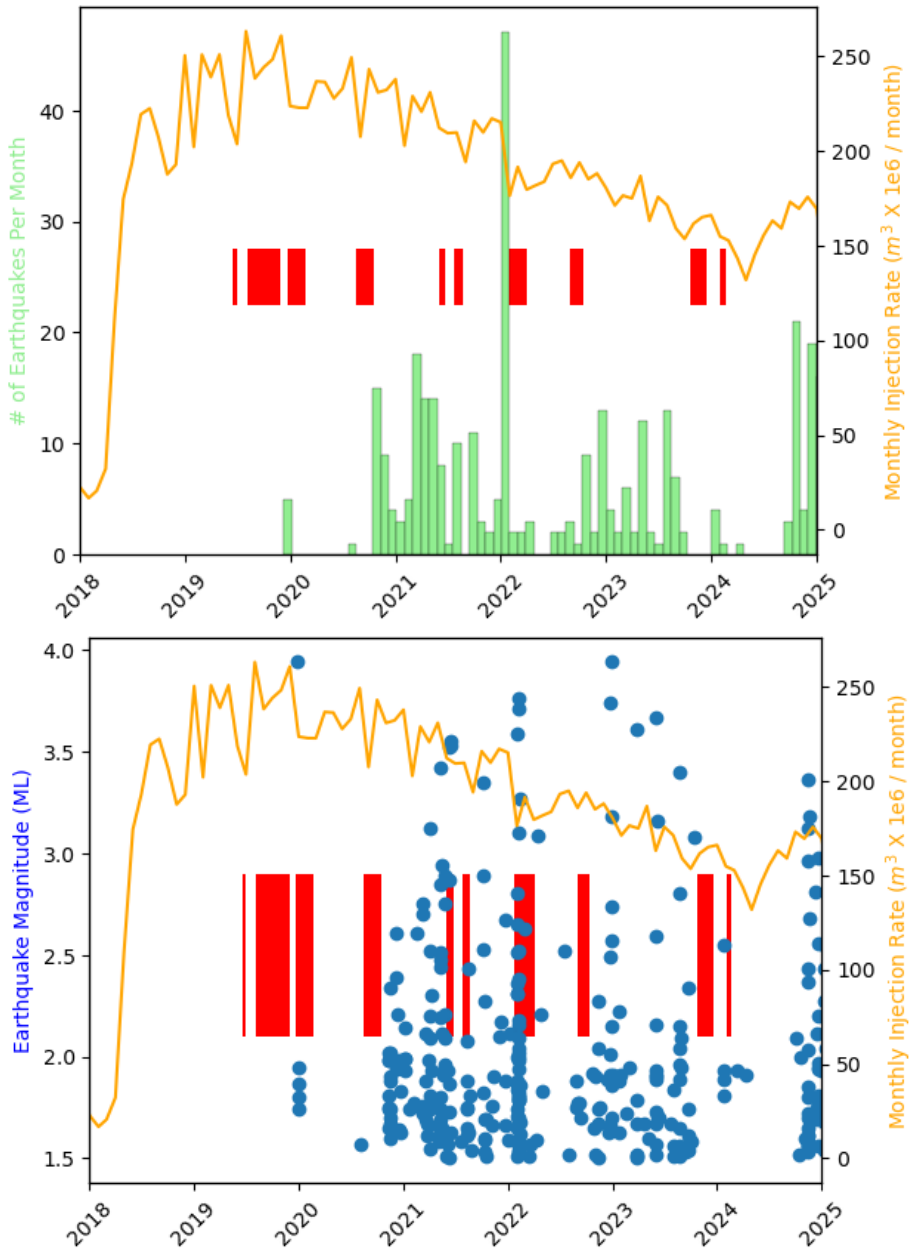
- The relocated earthquake catalog for Musreau Lake, AB
- Hydraulic fracturing wells are represented by red lines
- Water disposal wells are represented by orange lines





Central Musreau Lake

- Zoomed in view of the Central Musreau Lake cluster
- Blue dots represent seismicity
- Orange squares represent water disposal wells
- Red lines represent hydraulic fracturing wells
- Seismicity mainly correlated with water disposal wells



Central Musreau Lake

Monthly number of earthquakes above M 1.5 (green bars), monthly injection rates (orange curve), and active hydraulic fracturing dates (red horizontal bars) related to the Musreau Lake earthquake sequence.

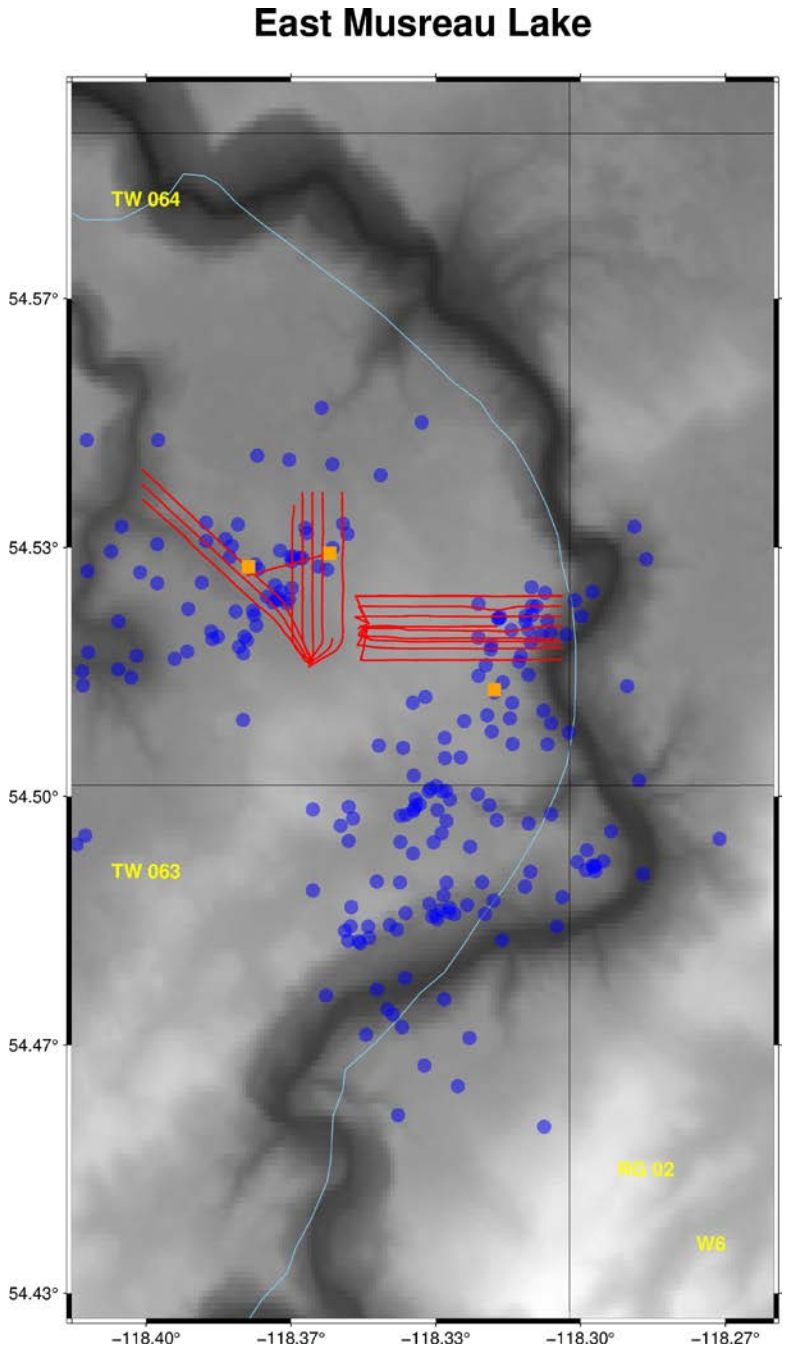
- Injection rates dropped after 2020
- A slight increase in injection rates towards the end of 2024

Magnitude of events (above M 1.5) over time (blue circles), monthly injection rates (orange curve), and active hydraulic fracturing dates (red horizontal bars) related to the Musreau Lake earthquake sequence.

- M 3.94 event at the end of 2019
- Decrease in seismicity from 2021 – 2024
- Increase in seismicity at the end of 2024

East Musreau Lake

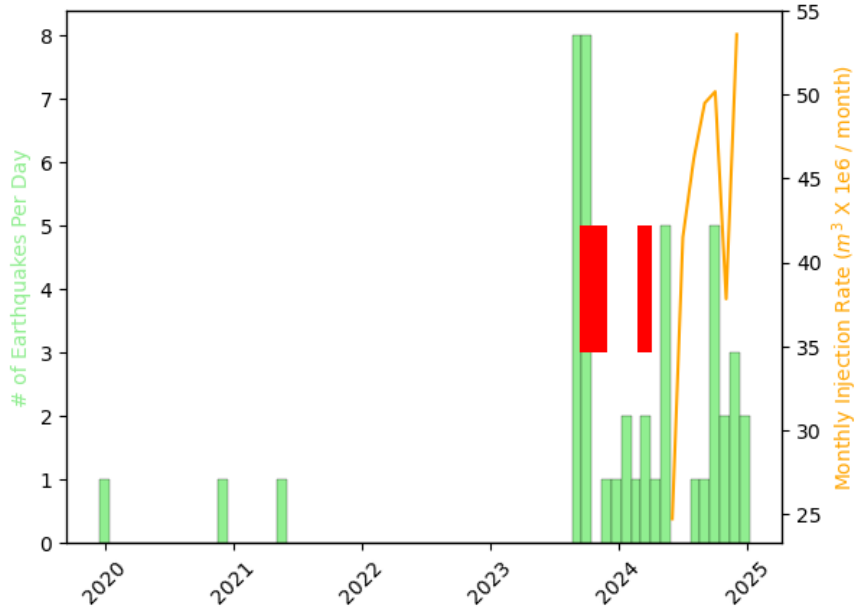
- Zoomed in view of the East Musreau Lake cluster
- Blue dots represent seismicity
- Orange squares represent water disposal wells
- Red lines represent hydraulic fracturing wells
- Both hydraulic fracturing and water disposal are correlated with seismicity



East Musreau Lake

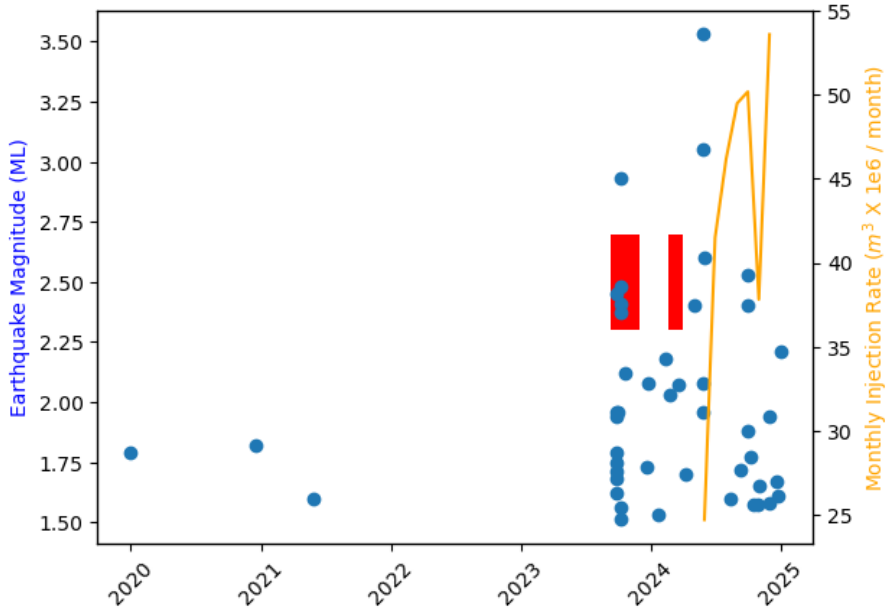
Monthly number of earthquakes above M 1.5 (green bars), monthly injection rates (orange curve), and active hydraulic fracturing dates (red horizontal bars) related to the Musreau Lake earthquake sequence.

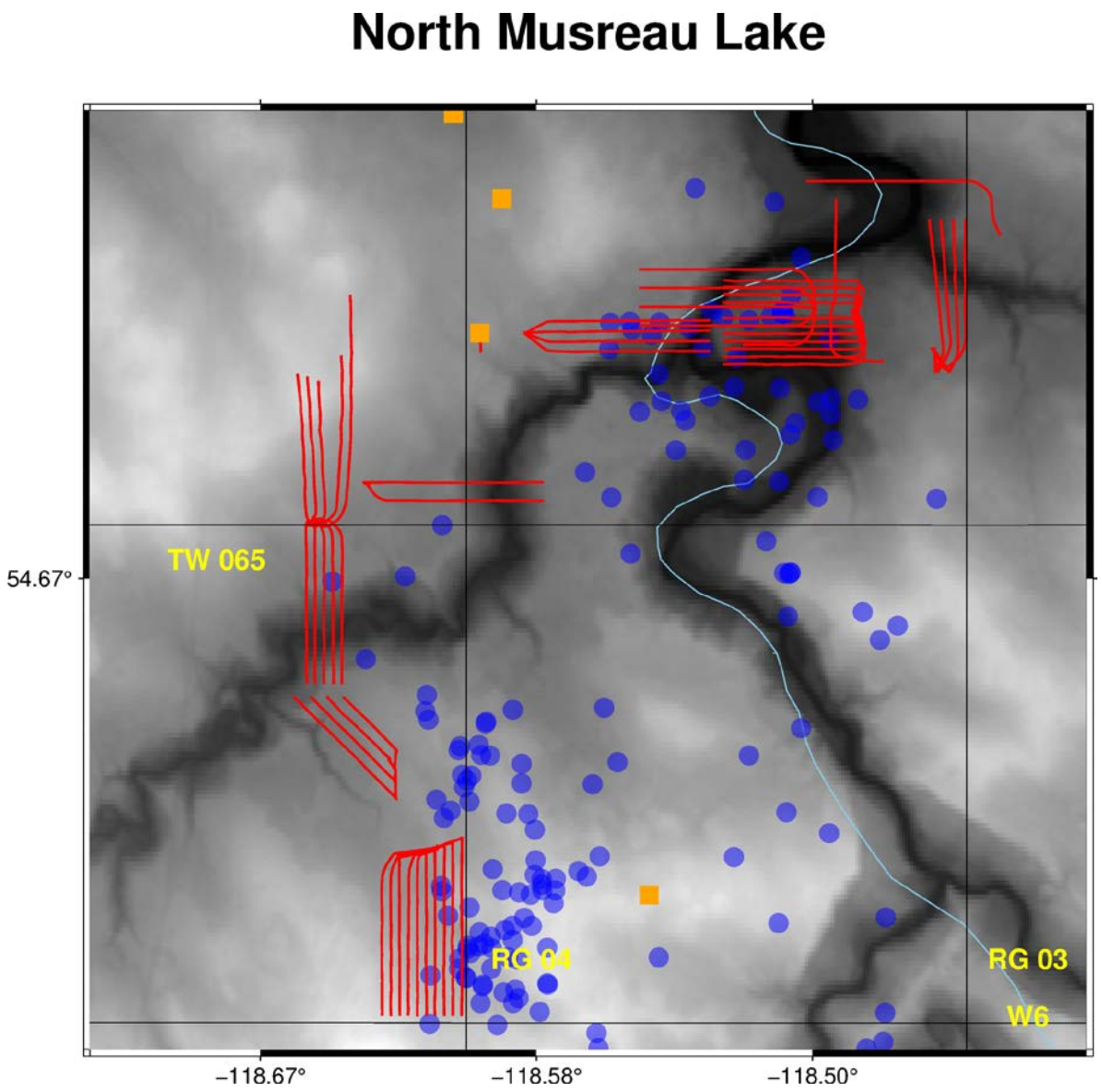
- Hydraulic fracturing activities occurred in 2023
- Disposal activities increased in early 2024
- A clear example of how hydraulic fracturing in the Montney may be causing seismicity



Magnitude of events (above M 1.5) over time (blue circles), monthly injection rates (orange curve), and active hydraulic fracturing dates (red horizontal bars) related to the east Musreau Lake earthquake sequence.

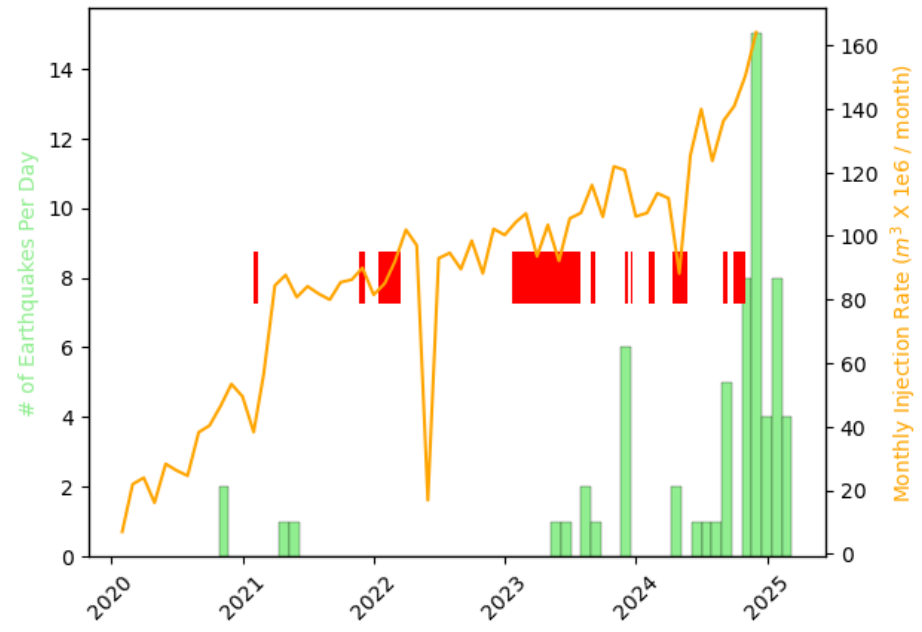
- Start of the seismicity in 2020
- Seismicity rate increased drastically in late 2023
- Increase in seismicity rate in late 2024

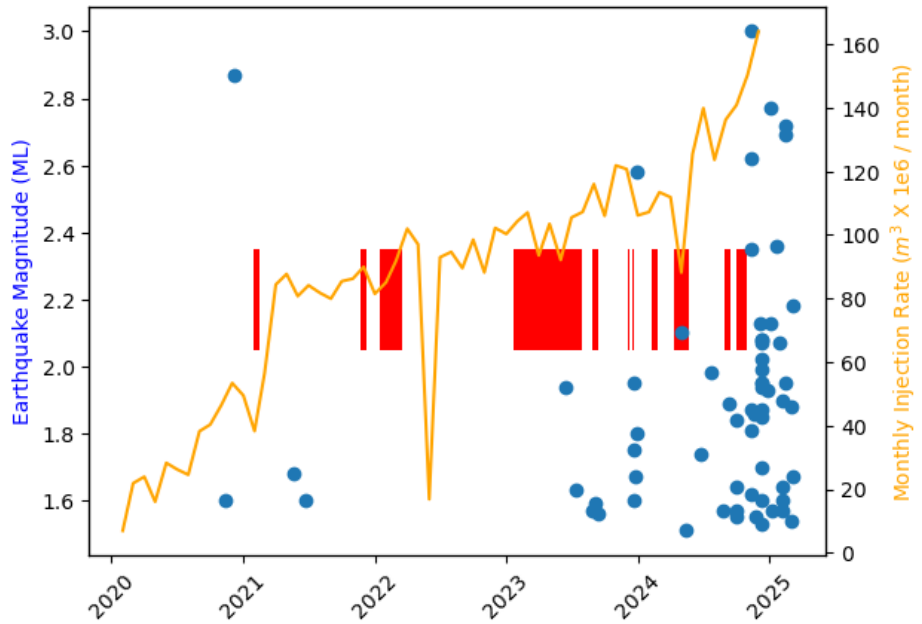




North Musreau Lake

- Zoomed in view of the North Musreau Lake cluster
- Blue dots represent seismicity
- Orange squares represent water disposal wells
- Red lines represent hydraulic fracturing wells
- Both hydraulic fracturing and water disposal appear to be correlated with seismicity





North Musreau Lake

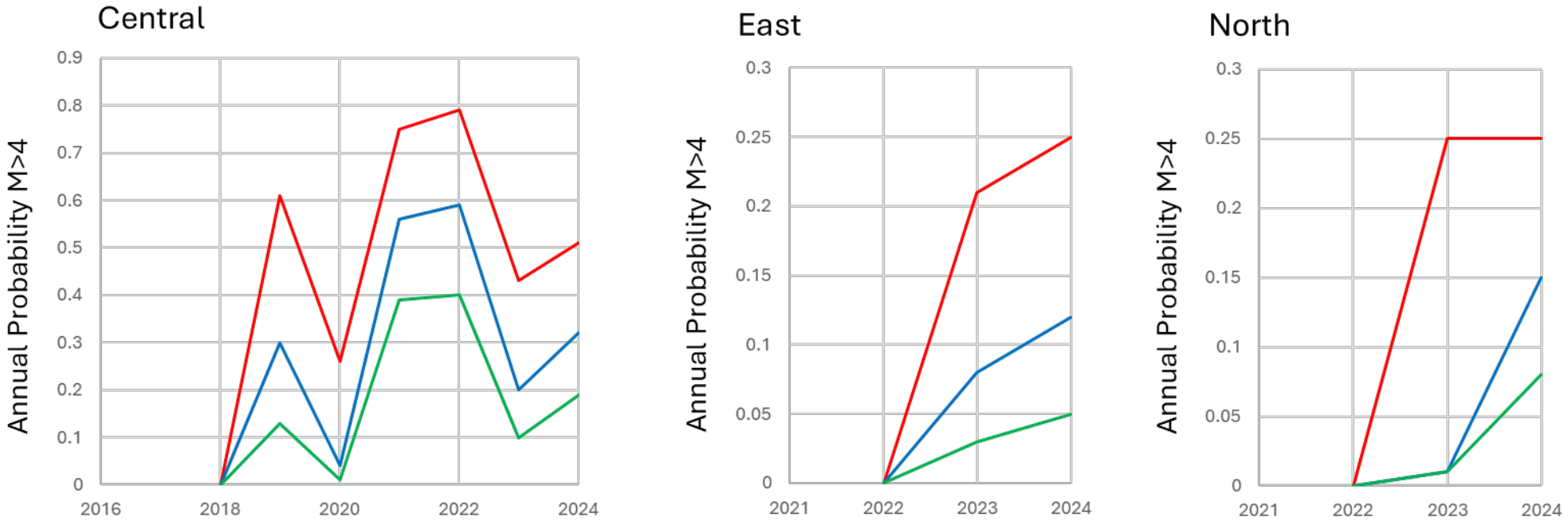
Monthly number of earthquakes above M 1.5 (green bars), monthly injection rates (orange curve), and active hydraulic fracturing dates (red horizontal bars) related to the Musreau Lake earthquake sequence.

- There has been a tendency to increase injection rates over time
- Corresponding increase in seismicity

Magnitude of events (above M 1.5) over time (blue circles), monthly injection rates (orange curve), and active hydraulic fracturing dates (red horizontal bars) related to the Musreau Lake earthquake sequence.

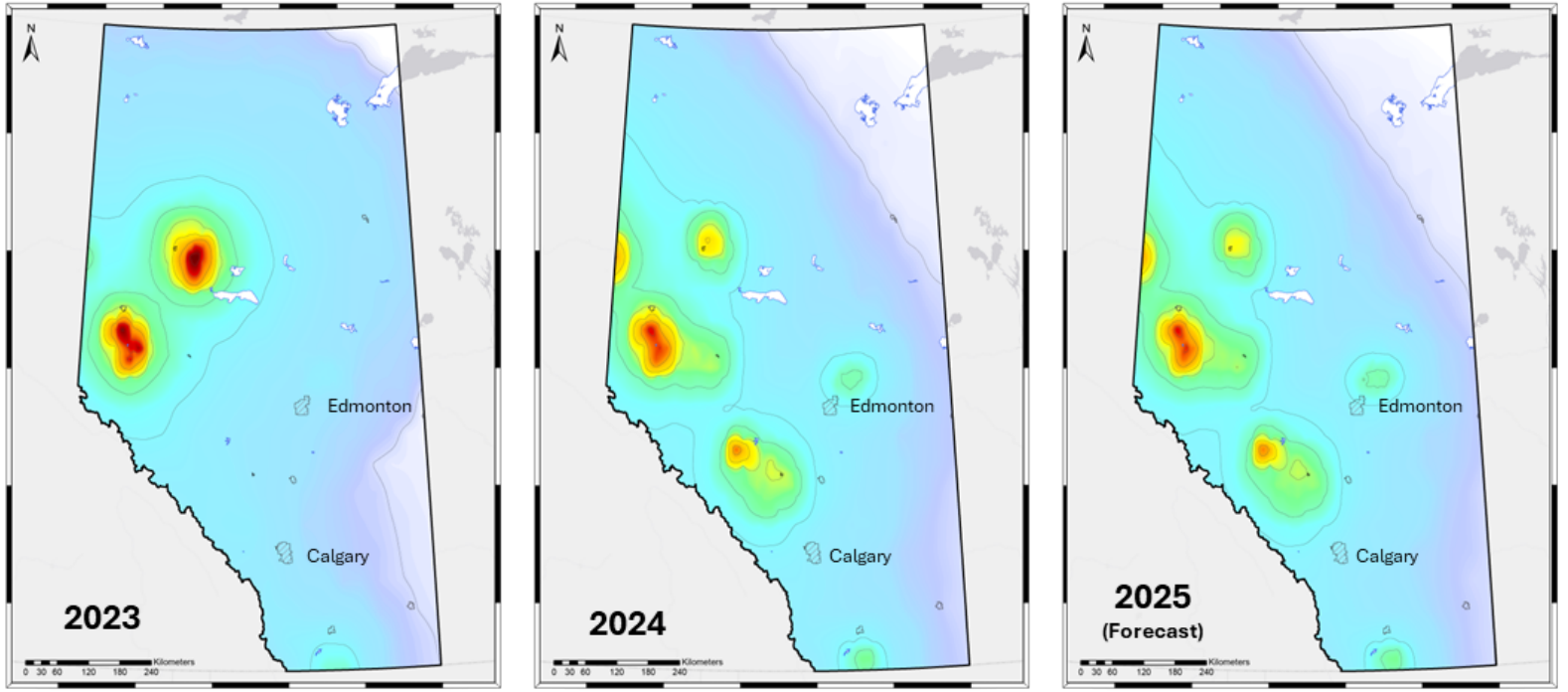
- Start of the seismicity in late 2020
- No events greater than M 3

Seismic hazard trends



- The red line represents the upper probability bound, while the green line represents the lower probability bound
- The greatest probability of an M > 4 event is in the Central Musreau Lake cluster
- The east and north clusters have a much lower probability of having an M > 4 event
- The probability of a large event varies over time, depending on industry activities
- Seismic hazard trends derived from PSHA

Probabilistic Seismic Hazard Assessment



Percieved Shaking	Not felt	Weak	Light	Moderate	Strong	Very Strong	Severe	Violent	Extreme
Peak Acceleration (%g)	< 0.17	0.17 - 1.4	1.4 - 3.9	3.9 - 9.2	9.2 - 18	18 - 34	34 - 65	65 - 124	> 124
Instrumental Intensity	I	II - III	IV	V	VI	VII	VIII	IX	X+

- A Monte Carlo simulation is performed using synthetic earthquake catalogs
- From these simulations, a map of predicted ground shaking is calculated

Peak ground acceleration (PGA as % of g) at a probability of 1% in 1 yr, from 2023 to 2025, for the province of Alberta. The equivalent modified Mercalli intensity scale is included.

Probabilistic Seismic Hazard Assessment

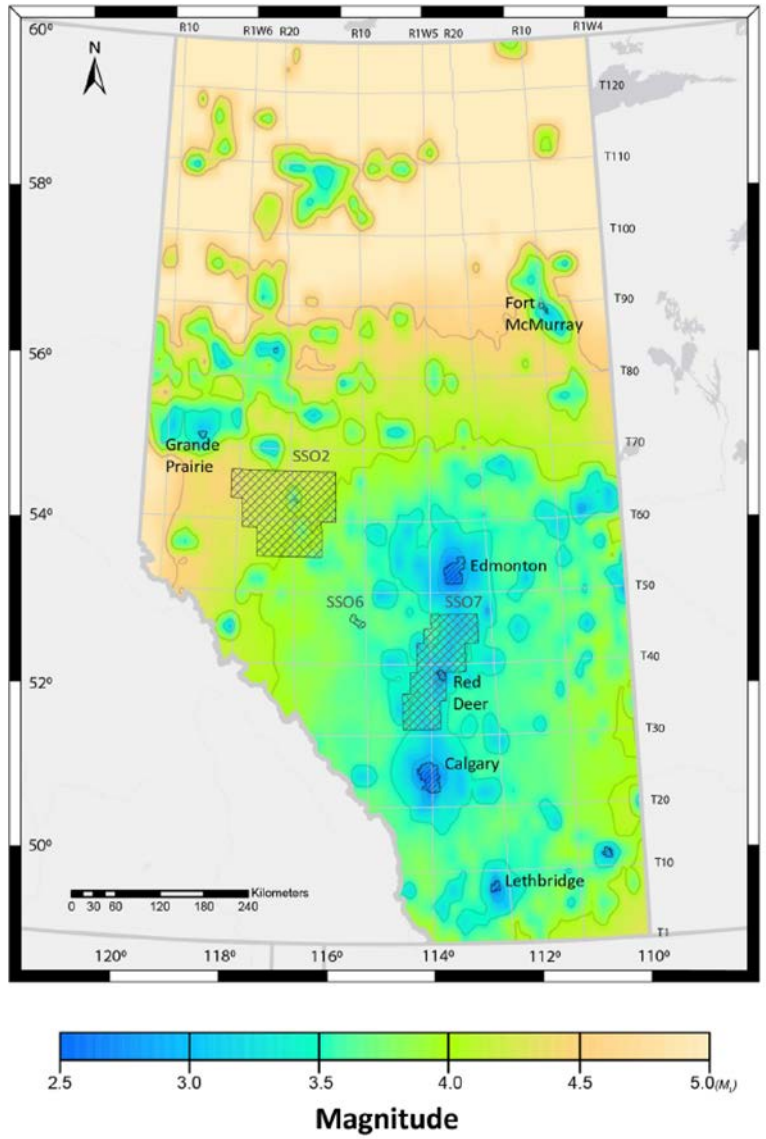
- The likelihood of events larger than magnitude M>4 in the Central Musreau Lake cluster peaked in 2022, with a 59% probability of reaching an earthquake larger than magnitude M>4 (mean case scenarios)

- For the years 2023 and 2024, the likelihood of events larger than magnitude M>4 decreased to 20% and 31%, respectively.

- The likelihood of events larger than magnitude M>4 in the East and North Musreau Lake clusters peaked in 2024, with an 12% and 15% probability of reaching an earthquake larger than magnitude M>4, respectively.

Environmental Protection Order

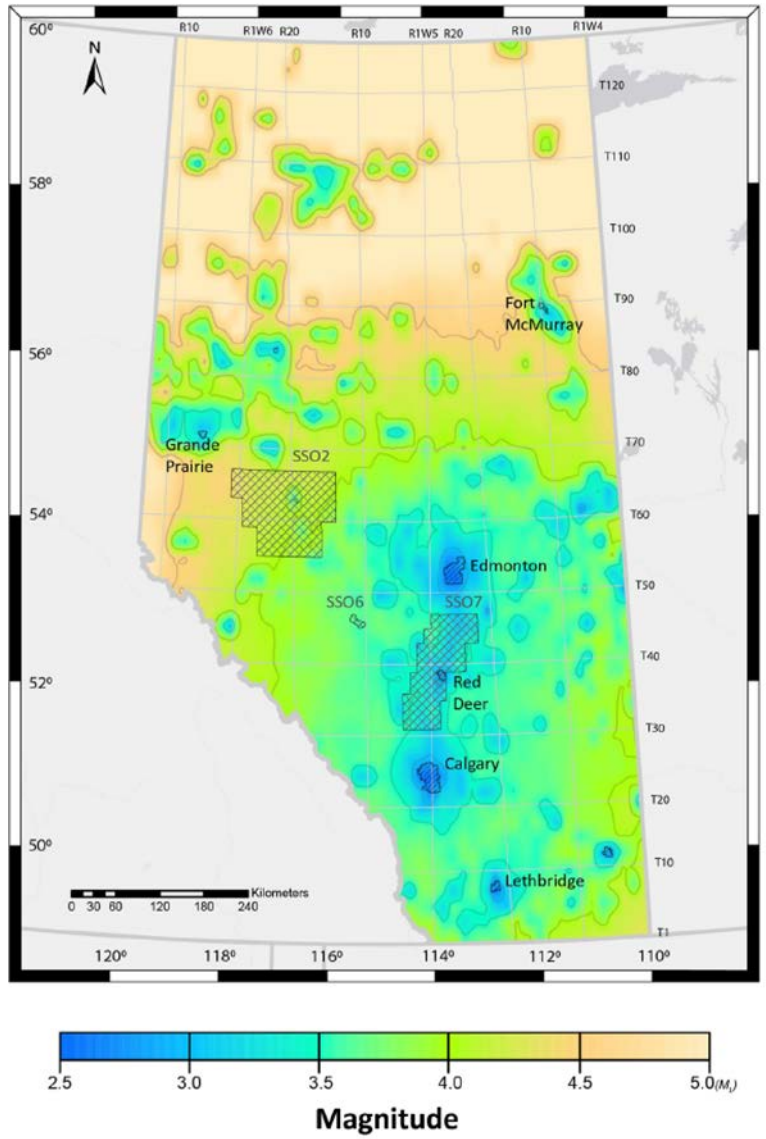
- In December 2019, a M 3.94 earthquake occurred in the central Musreau Lake cluster
- This made the AER aware of seismicity in this area
- There were few events after this until May 2021, when a swarm of seismicity was observed
  - An environmental protection order was issued, with operators mandated to follow a monitoring, mitigation and response plan
  - A red-light magnitude threshold of 4.2 was established, guided by iso-nuisance maps
  - The order was renewed after every M 3.5 event



Directive 65

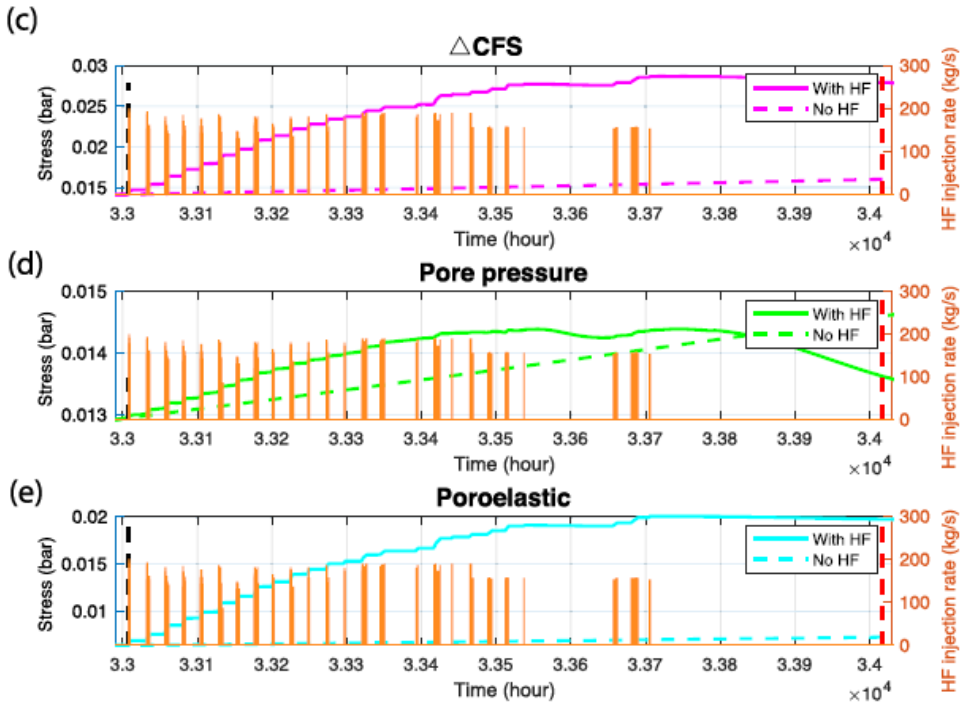
- In May 2024, the environmental protection order was lifted

- Directive 65 was released in November 2024
  - The directive applies to identified seismogenic disposal wells in the Musreau Lake area
  - Seismogenic disposal wells must follow a monitoring, mitigation, and response plan.
  - A traffic light protocol must be followed.



Combined Effects of HF and WD

- It has been suggested that some cases of induced seismicity may have been caused by a combination of HF and WD (Wang et al., 2023)
- It is possible that this situation is occurring in the North Musreau Lake cluster
- It is also possible that seismicity in the East Musreau Lake cluster may be caused by WD in other areas, further modelling is needed to test this hypothesis



Adapted from Wang et al., 2023

Questions?