Assessment of the Gold Creek and Kakwa Seismic Clusters in Relation to Disposal Activities in the Leduc Formation

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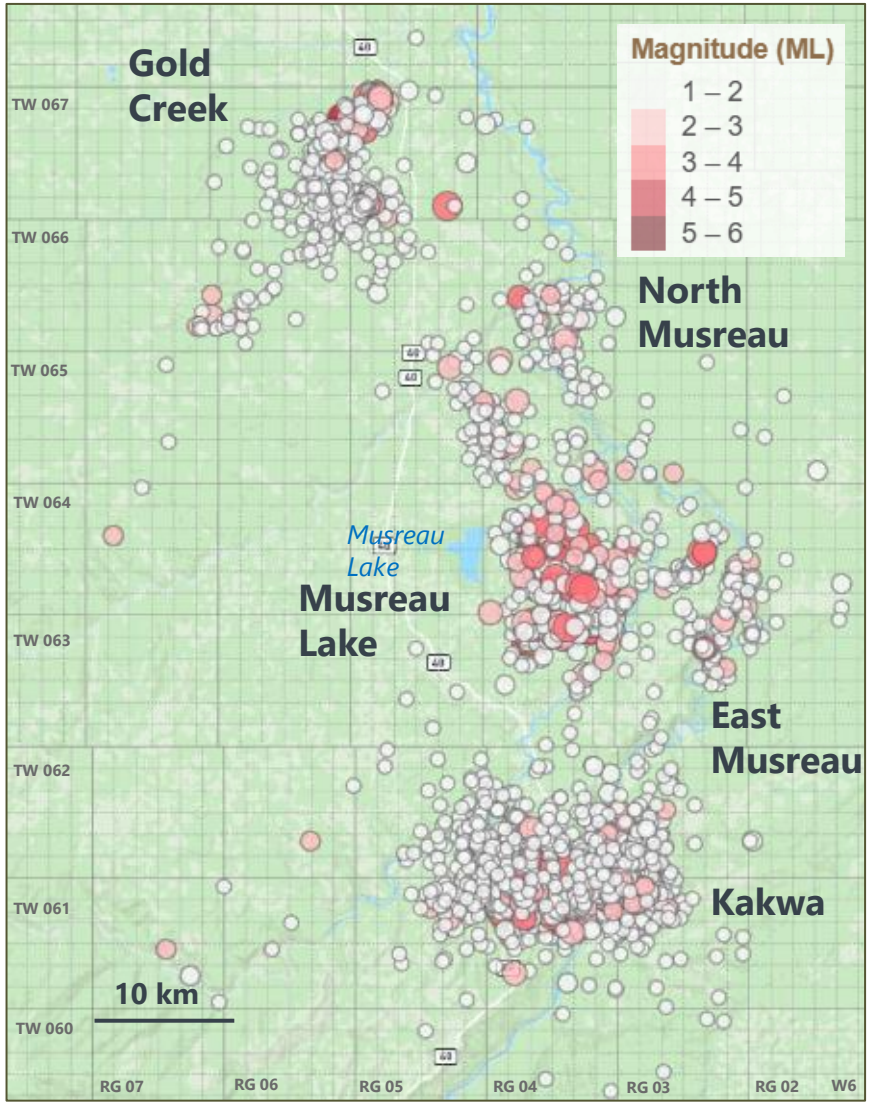
1. Introduction

- 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

2. Geological background

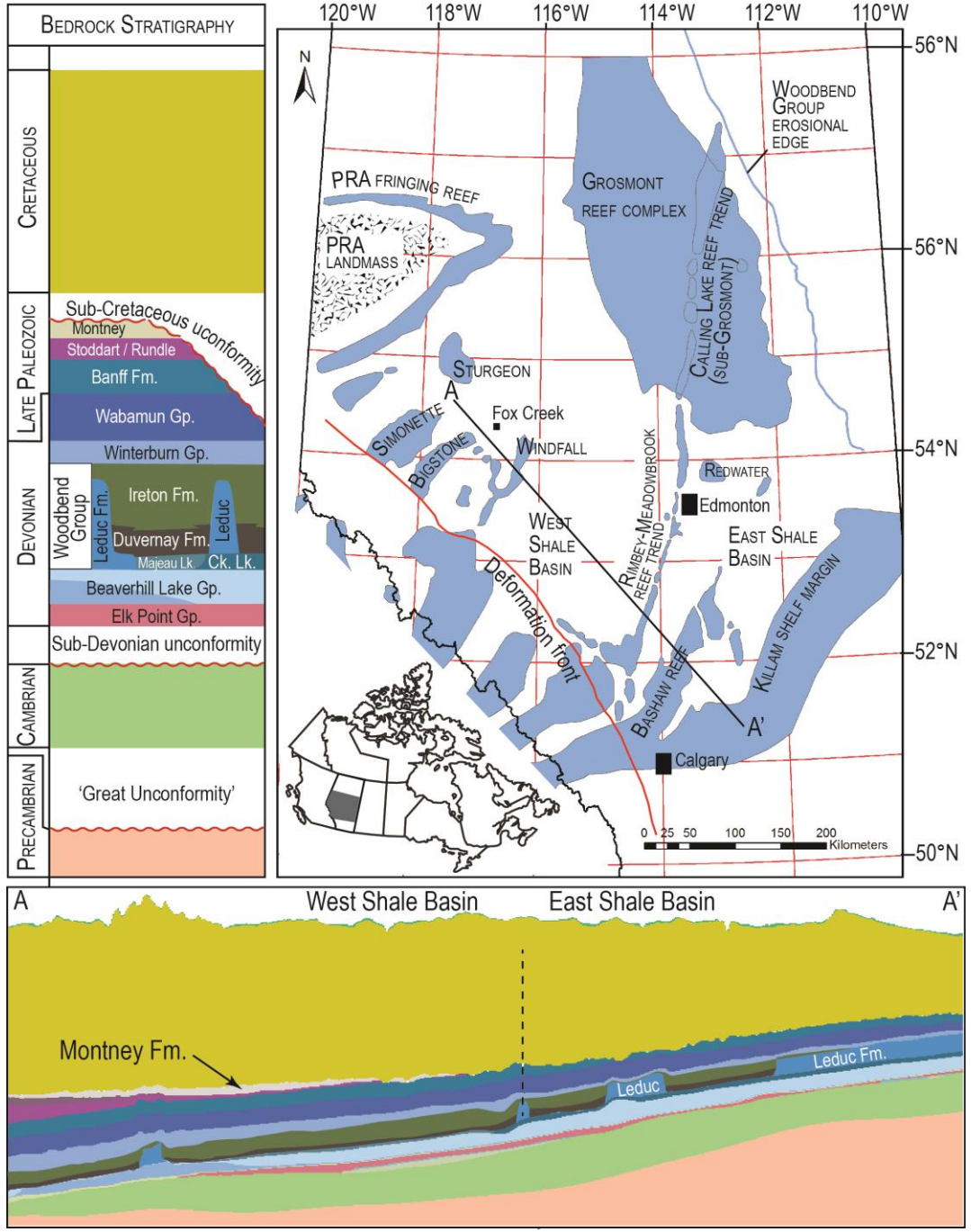
Induced seismicity has been associated with disposal in the Late Devonian Woodbend & Winterburn groups.

The Woodbend target is the Leduc Formation:

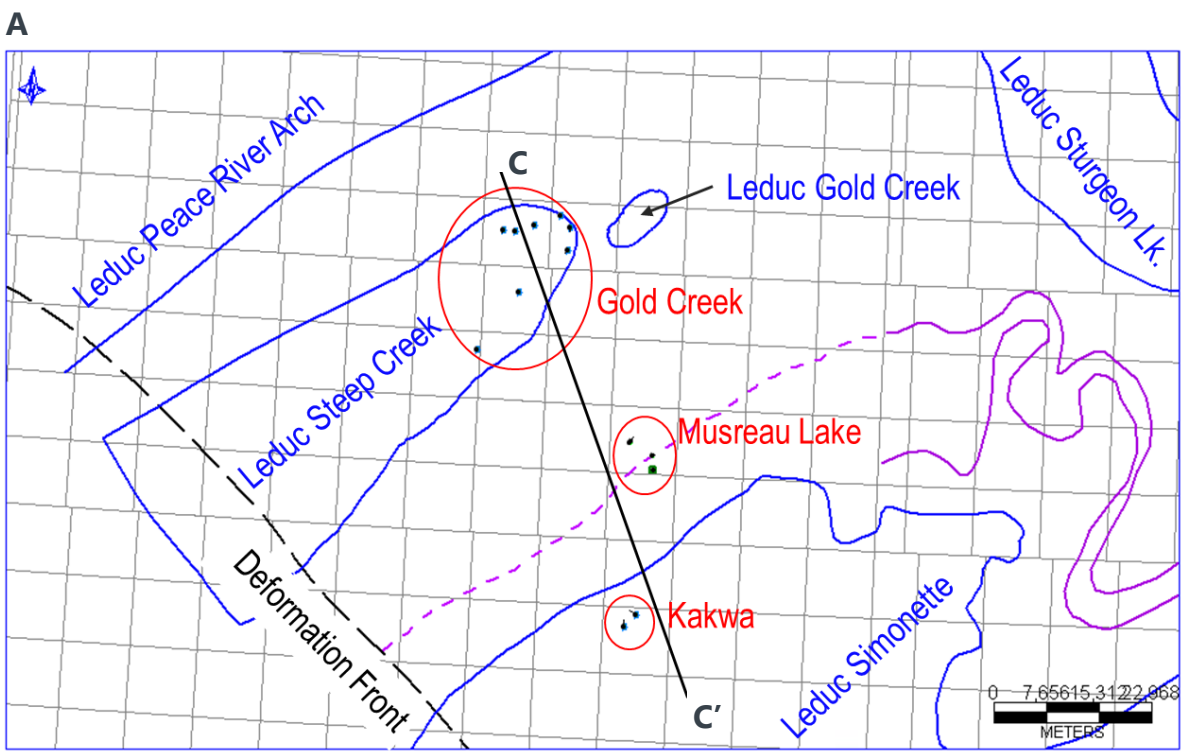
- Thick, shallow-water carbonate buildup (reef) encased in shales.
- We know very little about the Leduc Reefs in the study area due to a lack of well and core control (no hydrocarbon pools).

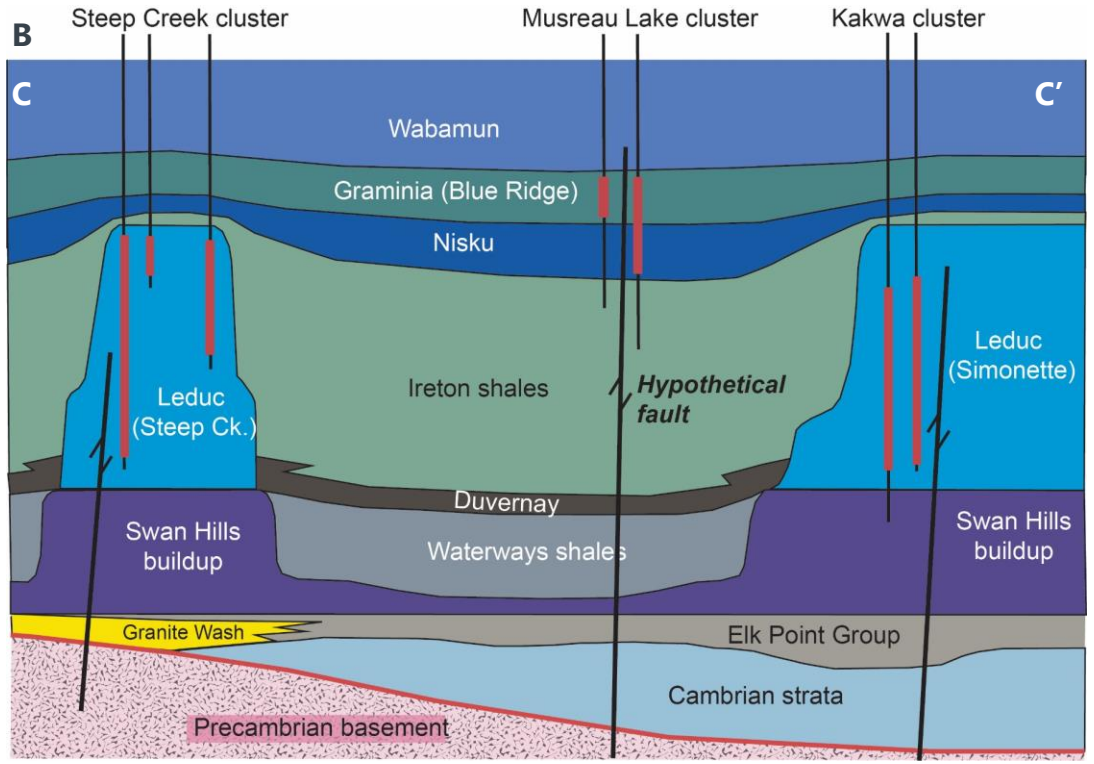
The Winterburn target is the Nisku and Graminia formations:

- 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.



2. Geological background

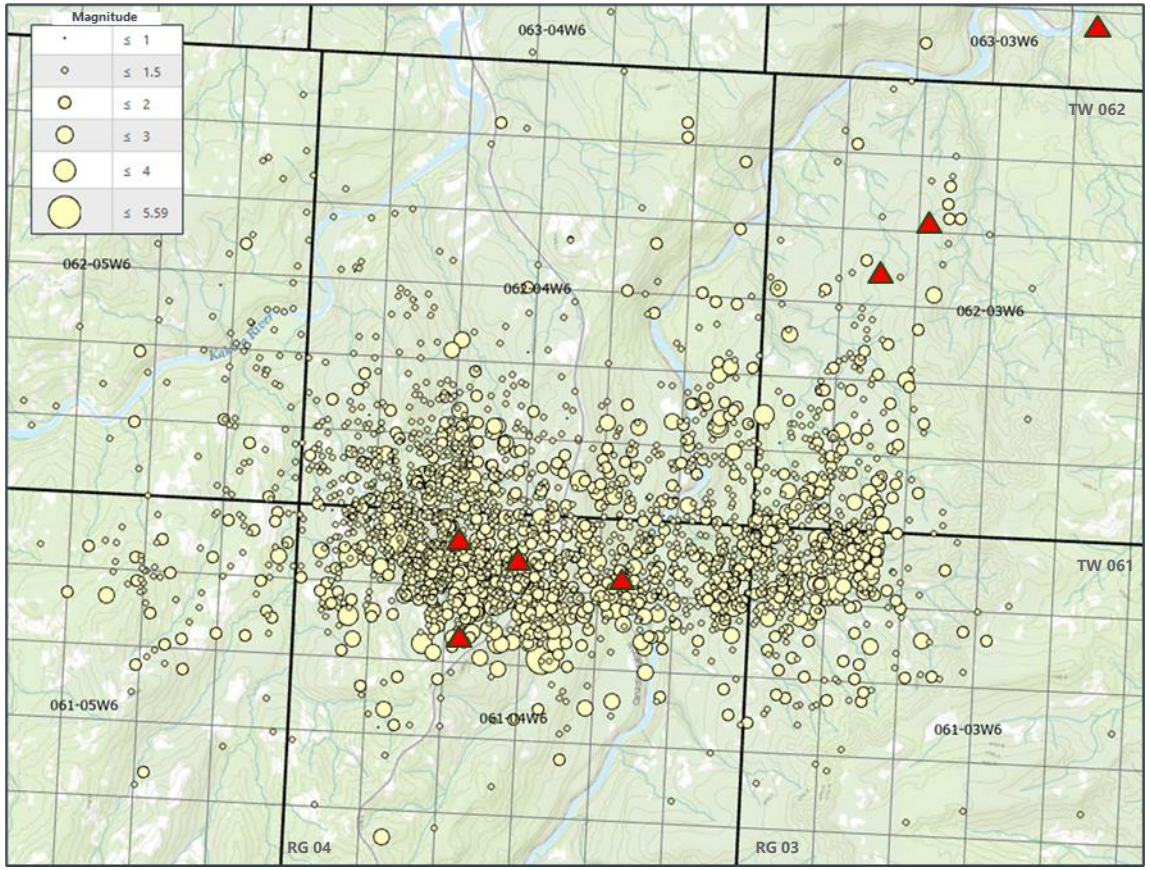




Map view (A) of the Leduc Formation reef edge and Swan Hills build-ups in the region south of Grande Prairie. Figure (B) shows a geological schematic from a northwest–southeast cross-section C-C′. Notice the seismogenic disposal activities in the Leduc reefs and the Winterburn Gp. (red bars on vertical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

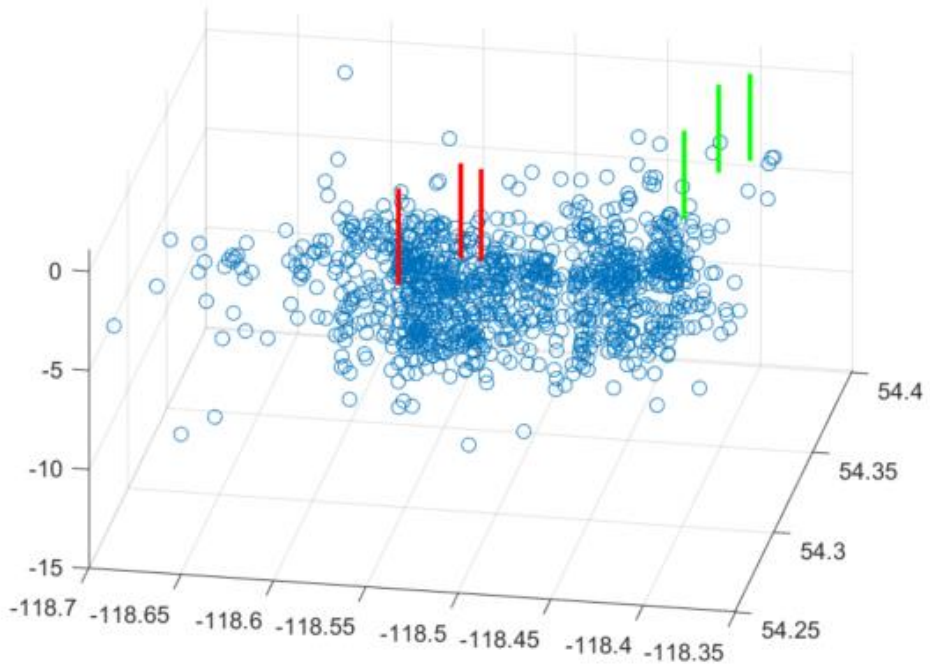
3. Kakwa earthquake sequence

- Over 2200 events have been detected in the Kakwa earthquakes sequence between March 2021 and April 2025.
- Magnitude range of the events: Ml=1.00 – Ml=5.08.
- Five events larger than M>3.5 have been recorded, including the M=5.08 (February 2025) and M=4.03 (October 2024).
- Depth of mainshock events: ≈ 6km (Basement).
- The cluster has been associated with disposal activity in the Leduc Fm.



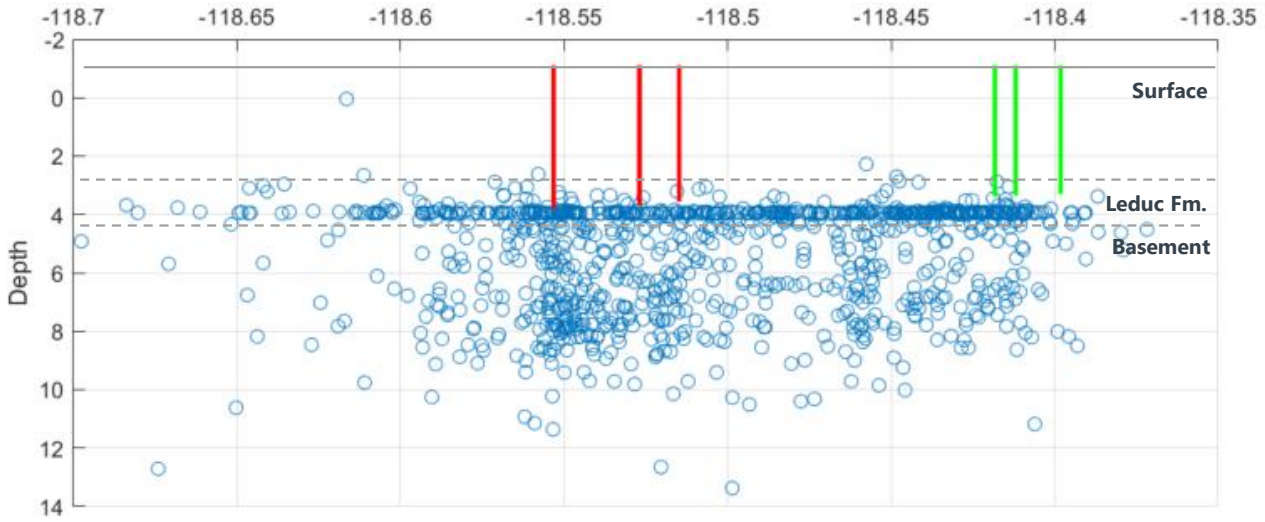
Location of the events for the Kakwa region, as well as the location of the positively correlated disposal wells injecting into the Leduc Formation (red triangles).

3-D view

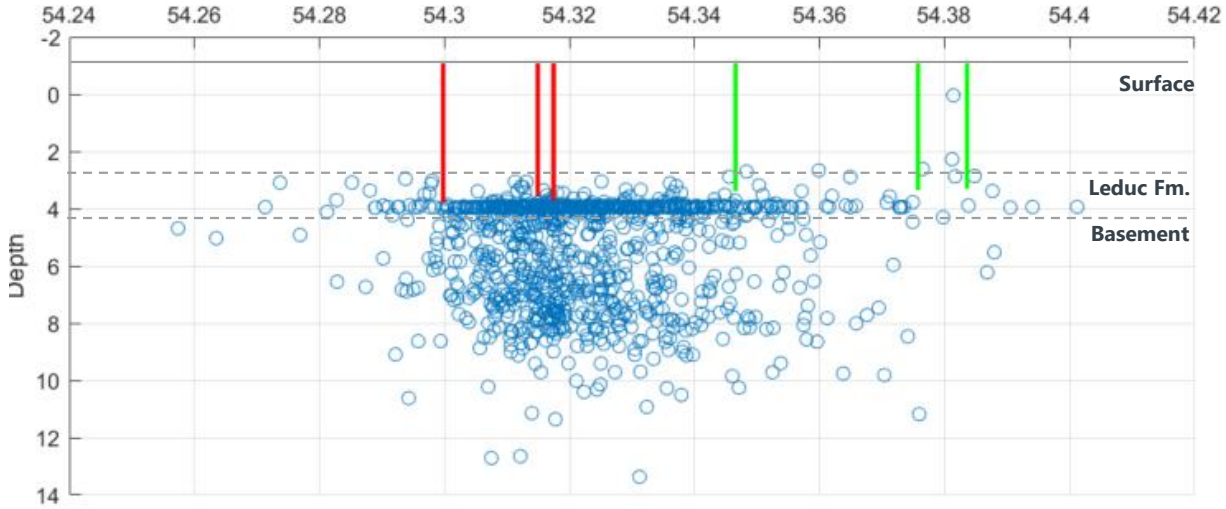


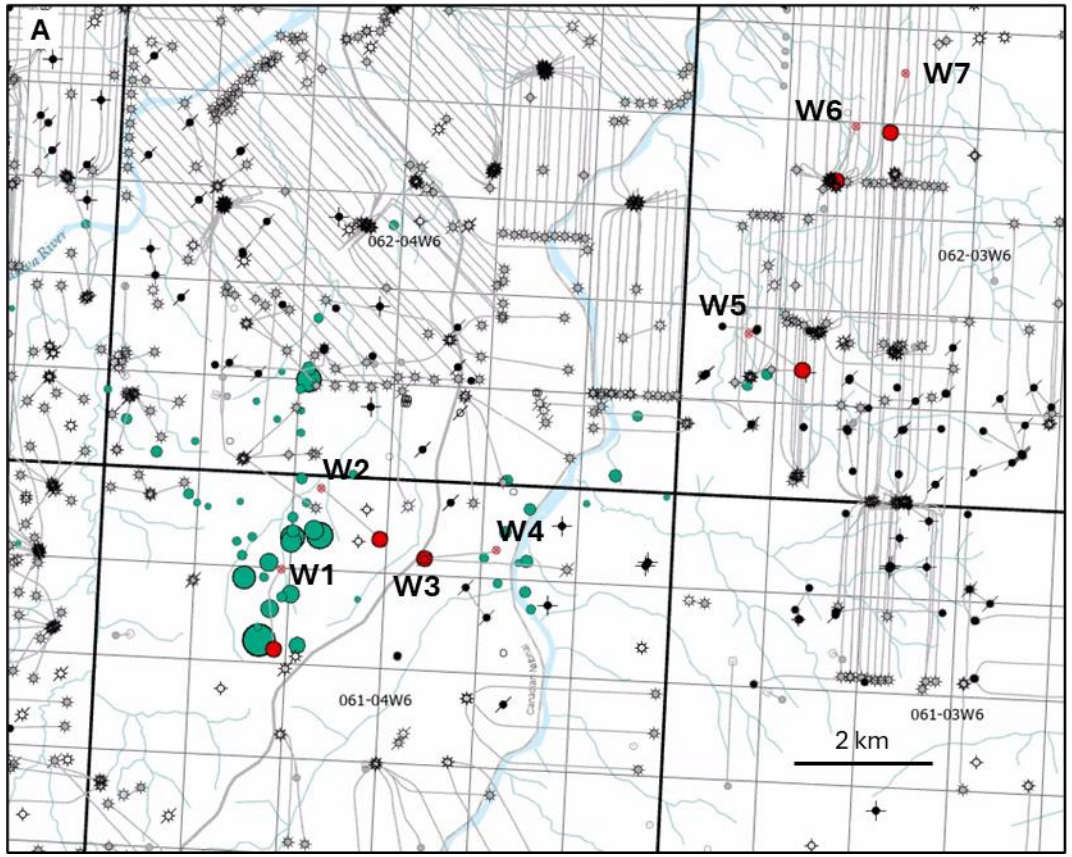
Relocated earthquake catalog, performing HypoDD, for the Gold Creek earthquake sequence. The figures shows a 3-D view, a west-east and south-north cross-section.

West-East cross-section

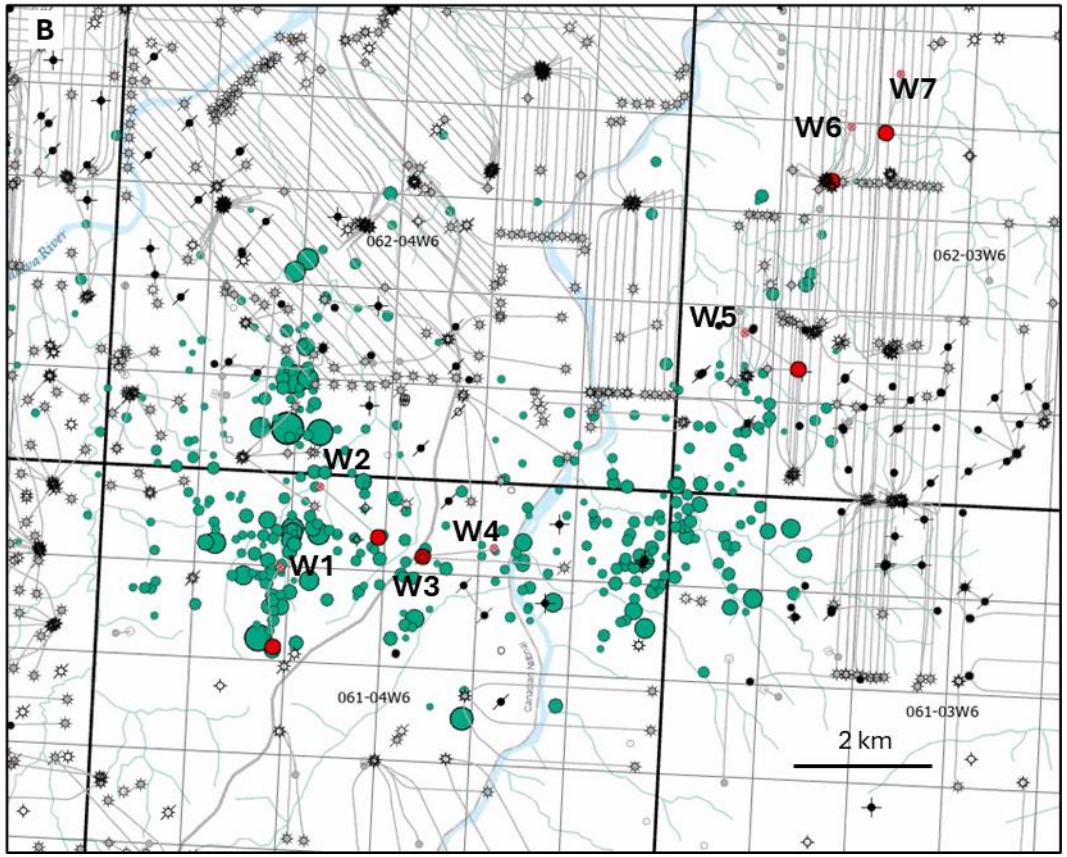


South-North cross-section





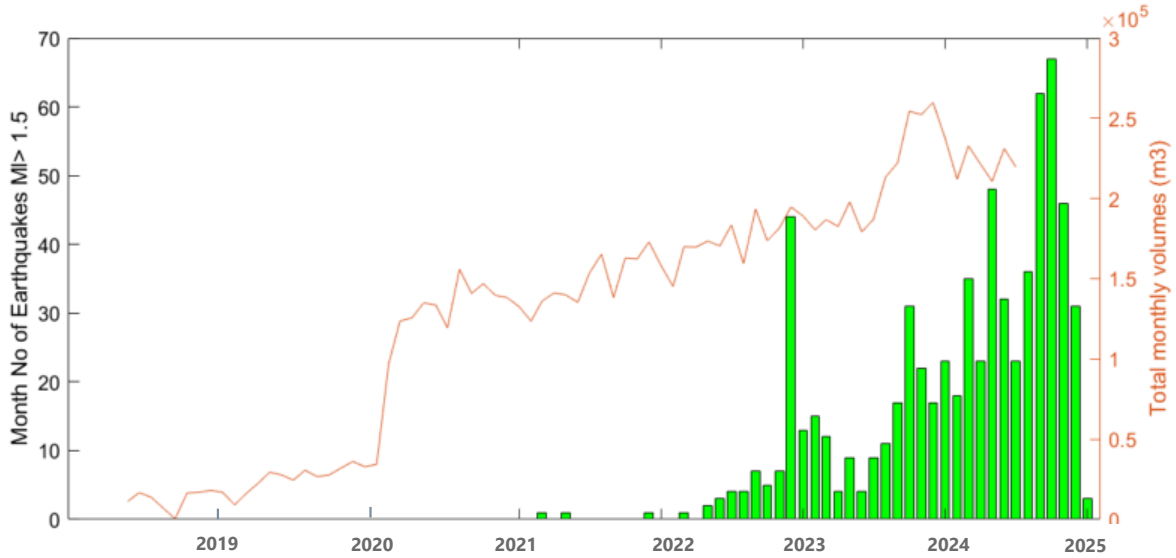
July 2022



August 2023

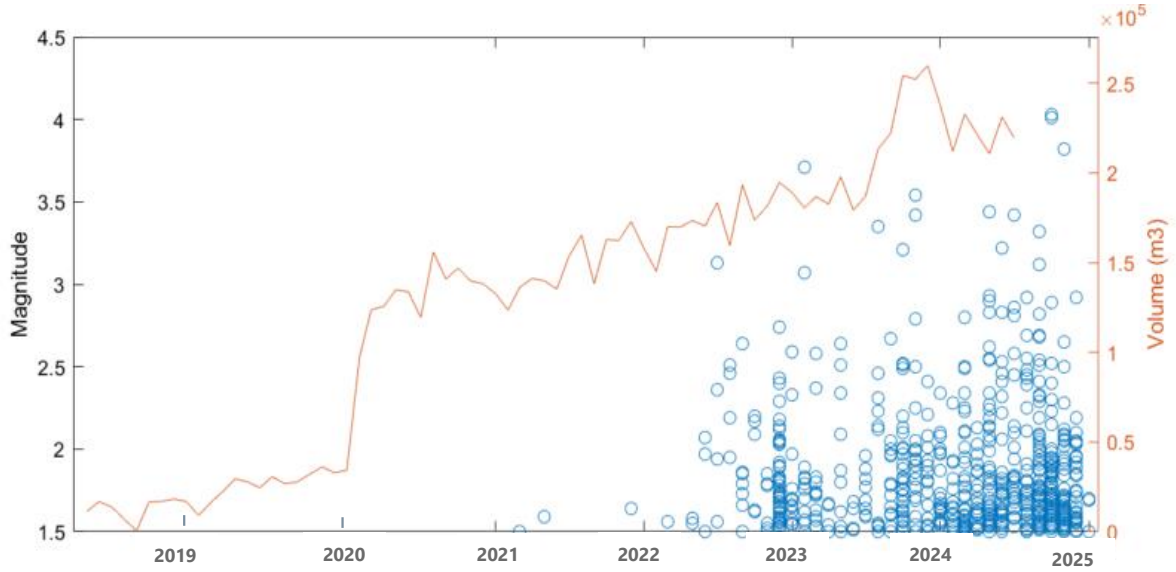
Comparison between the seismicity (green dots) in the Kakwa area up to July 2022 (A) and August 2023 (B). The disposal wells in the area (injecting into the Leduc Fm) are shown as red circles. Notice the expansion of the seismicity towards the East and North. The thin black horizontal lines refer to other activities, mostly horizontal wells in the Montney Fm.

Operational trends



Monthly number of earthquakes (green bars, earthquakes larger than magnitude M>1.5) and monthly injection rates (orange curve) from seismogenic disposal activities related to the Kakwa earthquake sequence.

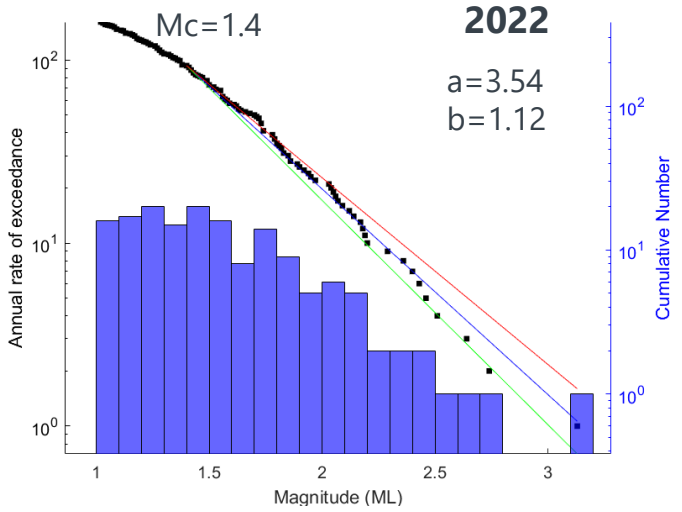
- There has been a tendency to increase injection rates over time.

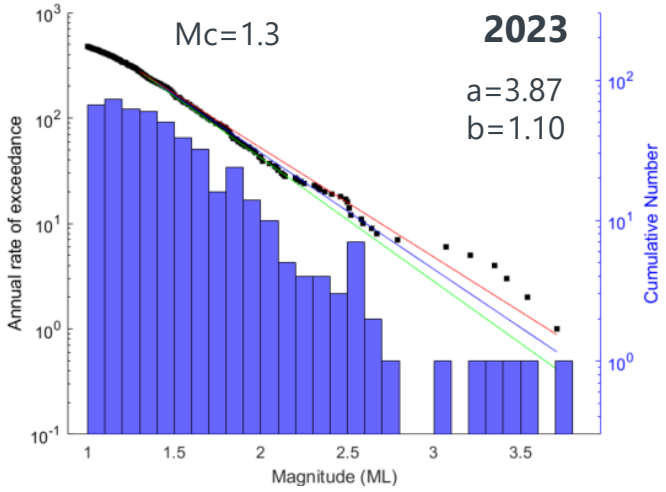


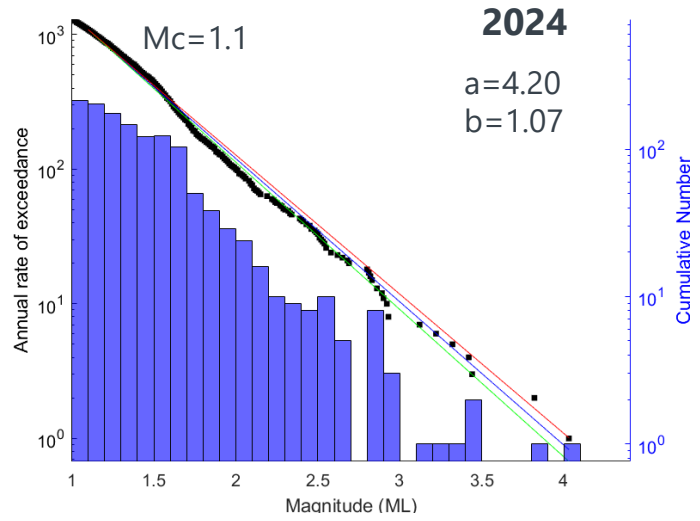
Magnitude of events over time (blue circles) and monthly injection rates (orange curve) from seismogenic disposal activities related to the Kakwa earthquake sequence.

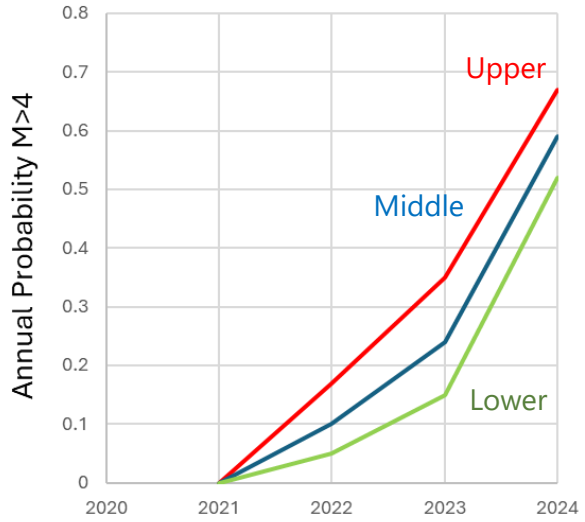
- Start of the seismicity in March 2021
- First event M>3 in July 2022
- First events M>3.5 in February 2023

Seismic hazard trends





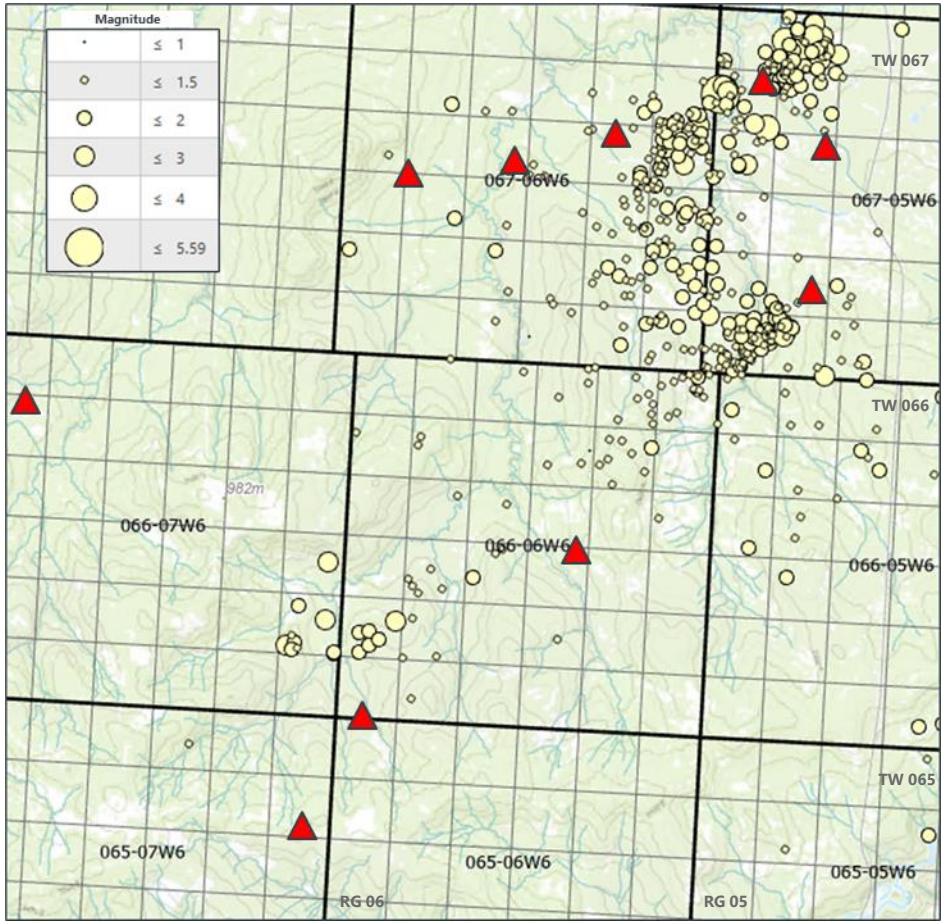




- Annual b-values remain relatively constant (gentle decrease). Annual a-values keep increasing (increase in the overall number of earthquakes).
- The annual likelihood of events larger than M>4 increases over time: 1% in 2022, 24% in 2023 and 59% in 2024.
- The annual likelihood of events larger than M>4 before the first events M>4 was 34%. The red line represents the upper probability bound, while the green line represents the lower probability bound.
- If increasing operational trends continue, we would expect an increasing number of events and seismic hazard.

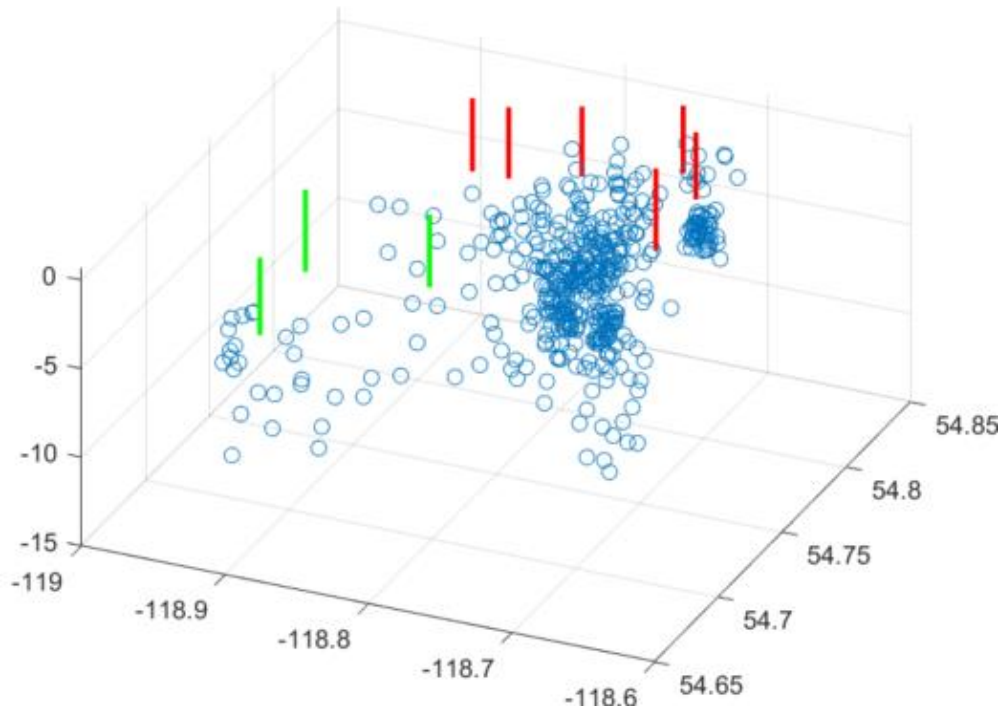
4. Gold Creek earthquake sequence

- Over 450 events have been detected in the Gold Creek earthquakes sequence between August 2019 and April 2025.
- Magnitude range of the events: Ml=1.00 – Ml=4.50.
- Six events larger than M>3.0 have been recorded, including the M=4.50 (October 2024).
- Depth of mainshock events: ≈ 6km (Basement).
- The cluster has been associated with disposal activity in the Leduc Fm.

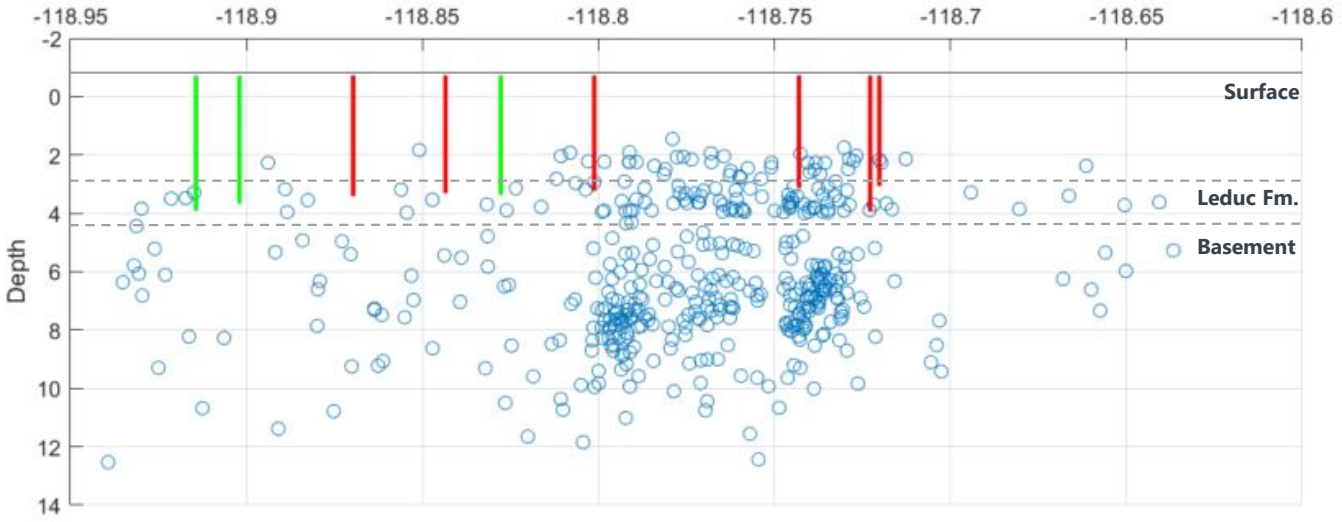


Location of the events for the Gold Creek region, as well as the location of the positively correlated disposal wells injecting into the Leduc Formation (red triangles).

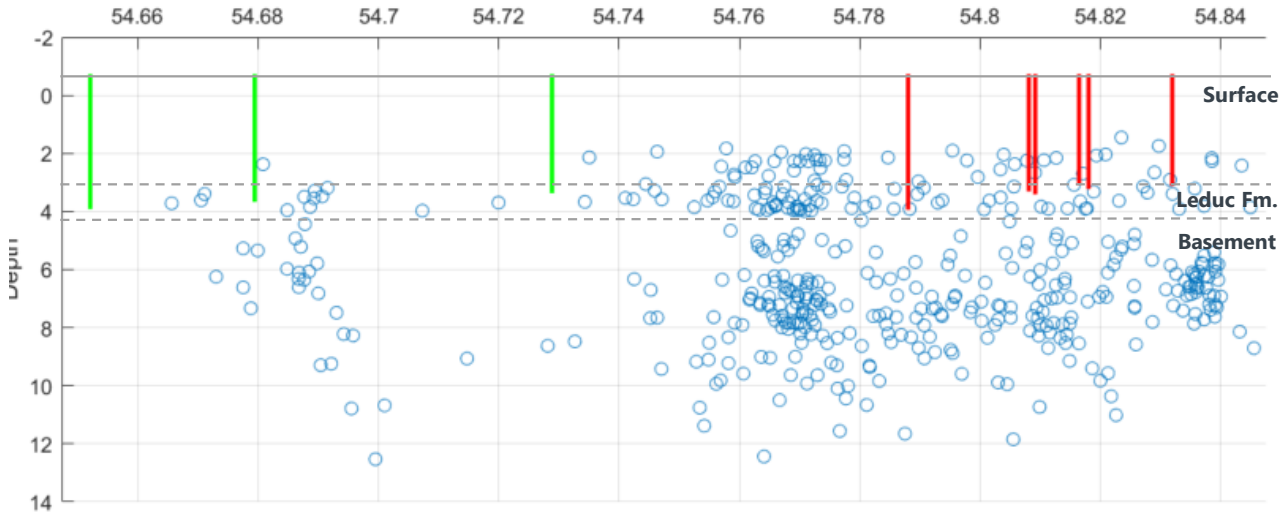
3-D view



West-East cross-section



South-North cross-section



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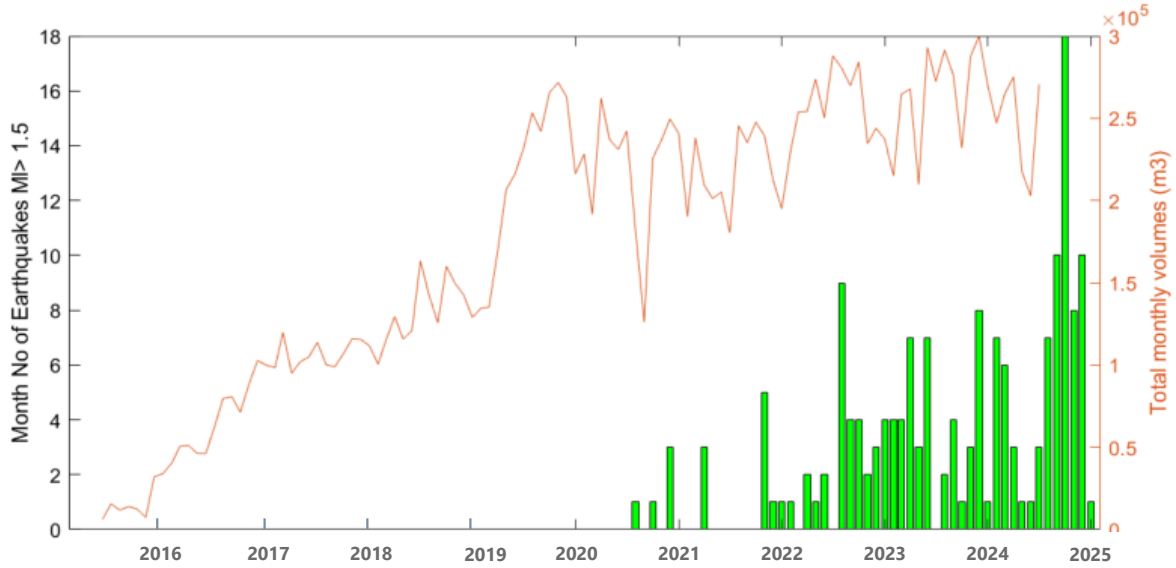
Operational trends



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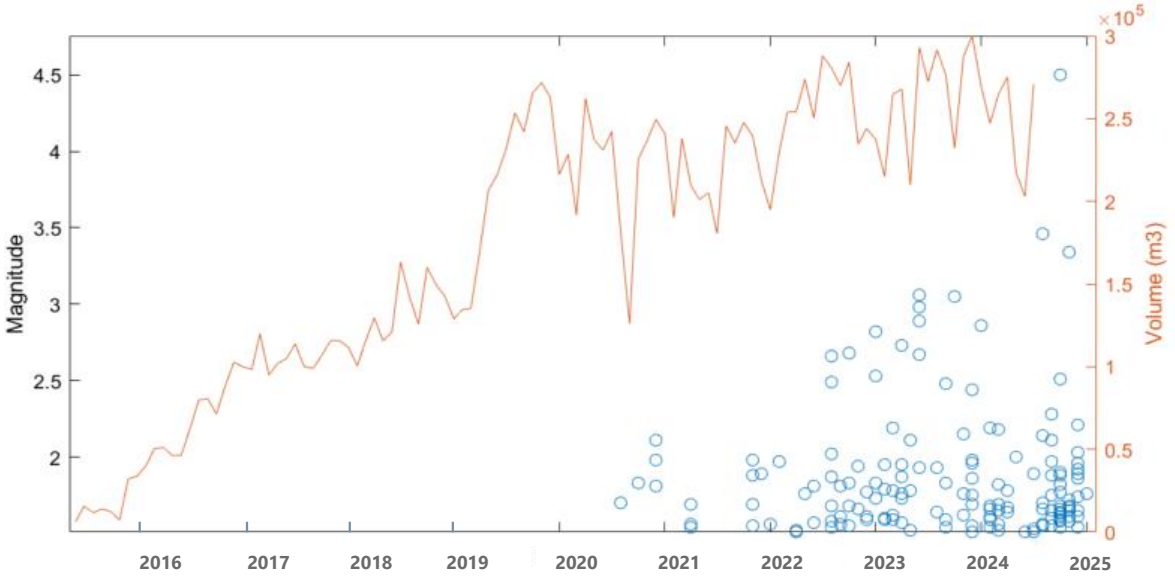
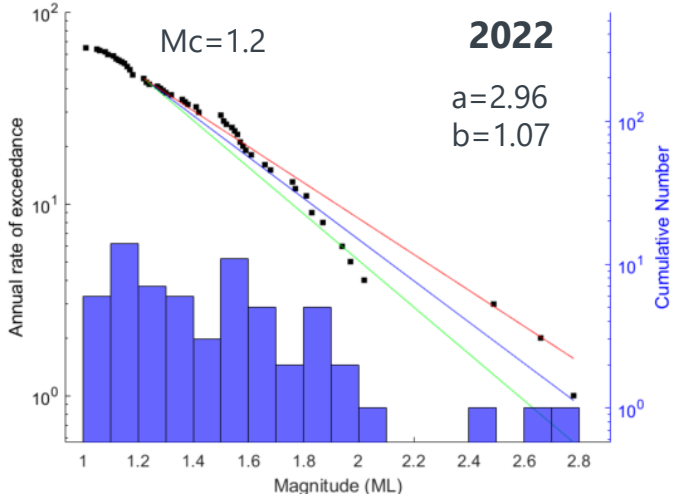
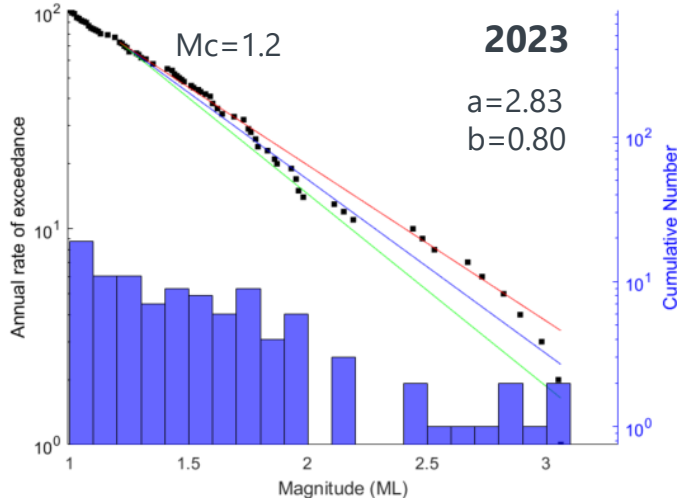


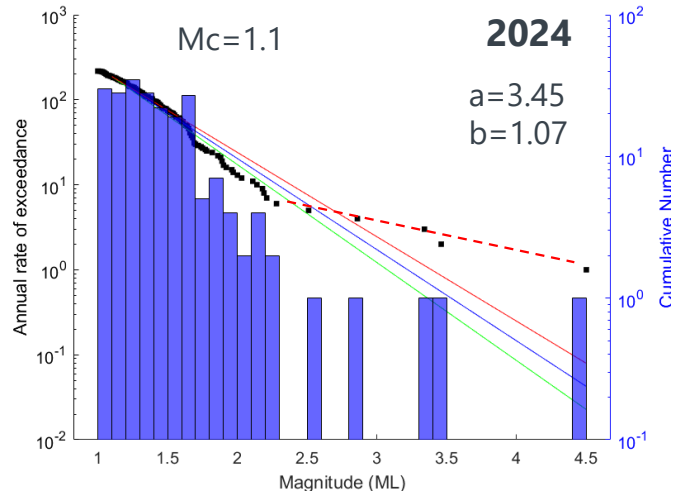
Magnitude of events over time (blue circles) and monthly injection rates (orange curve) from seismogenic disposal activities related to the Gold Creek earthquake sequence.

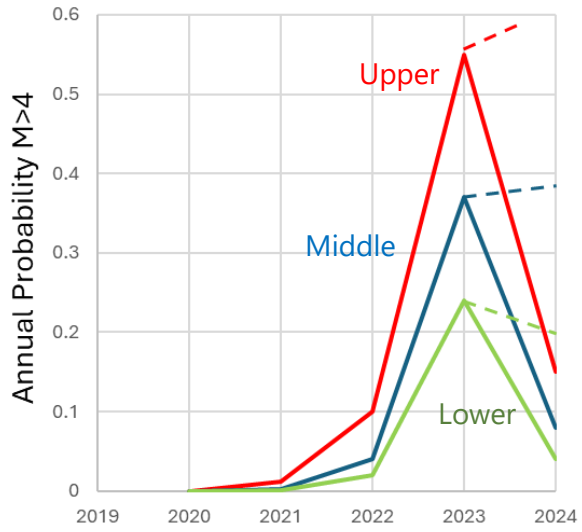
- First event M>3 in June 2023
- First events M>4 in October 2024. M=3.46 in August 2024.

Seismic hazard trends



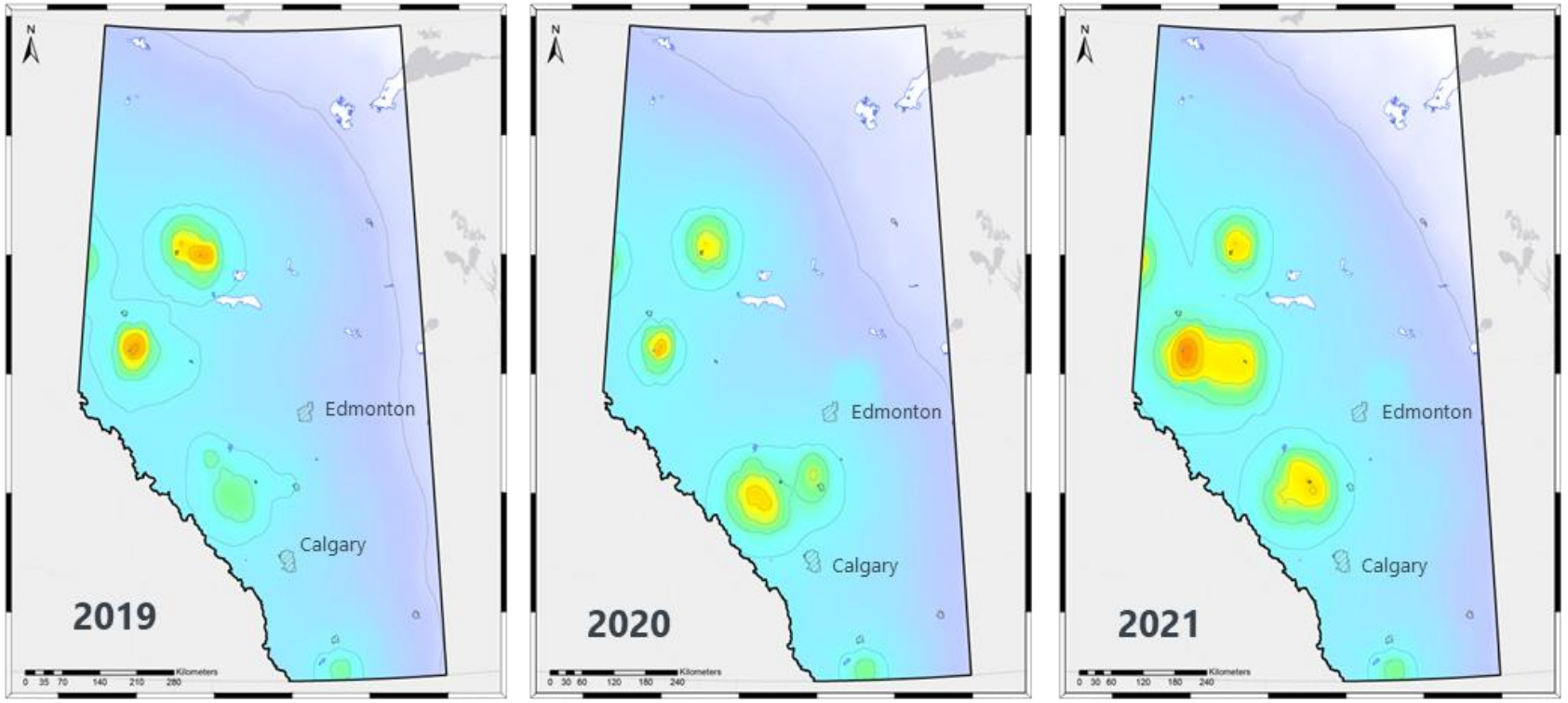






- Annual b-values remain relatively constant. Annual a-values keep increasing (increase in the overall number of earthquakes).
- The annual likelihood of events larger than M>4 increases over time: <1% in 2021, 4% in 2022, 37% in 2023 and 8% (38% considering bimodality) in 2024.
- For the year 2024, we observe a bimodality in the magnitude frequency distribution.
- If increasing operational trends continue, we would expect an increasing number of events and seismic hazard.

5. Short-term PSHA maps for Alberta



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+

Peak ground acceleration (PGA as % of g) at a probability of 1% in 1 yr, from 2019 to 2021, for the province of Alberta. The equivalent modified Mercalli intensity scale is included.

Largest seismic hazard estimated south of the Grande Prairie region:

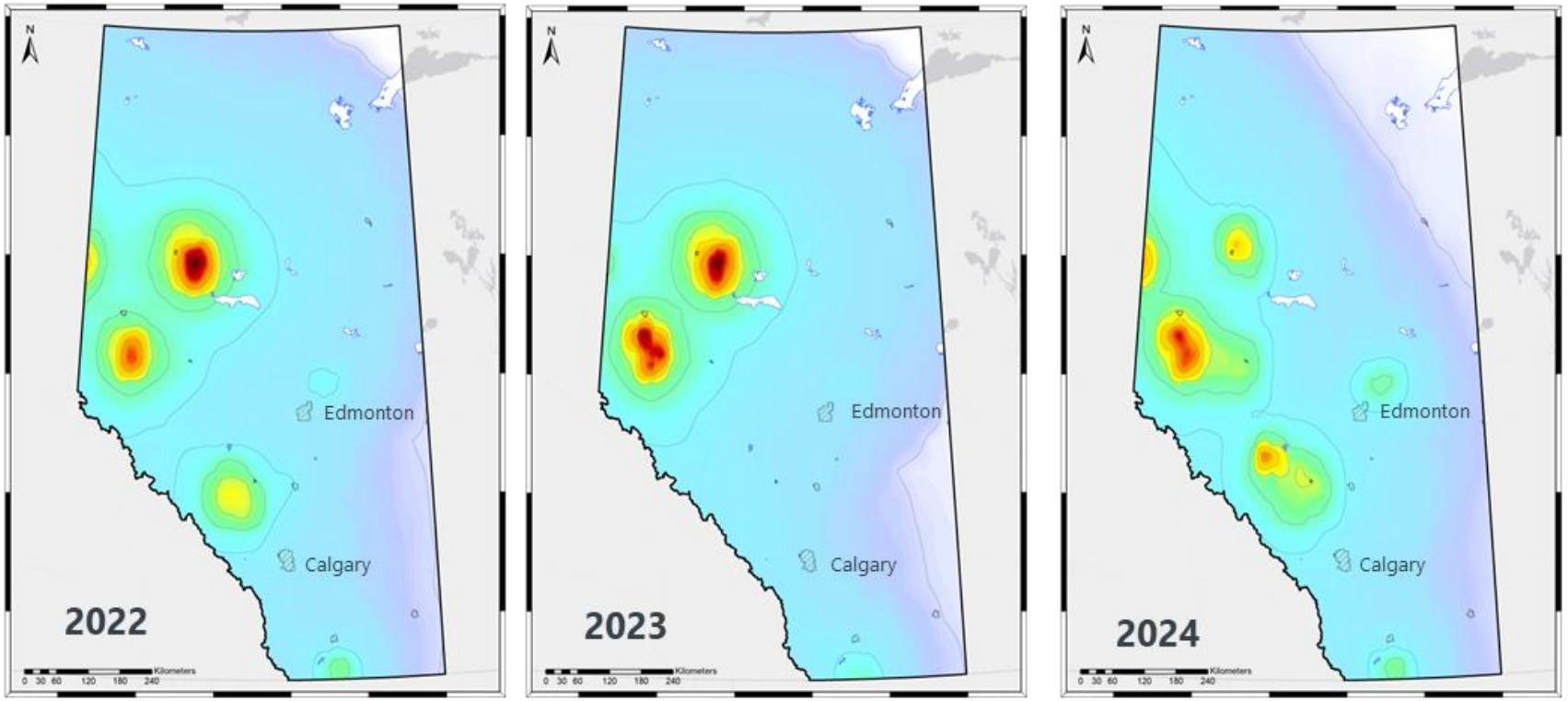
2019: 40% g at a probability of 1% in 1 yr

2020: 27% g at a probability of 1% in 1 yr

2021: 48% g at a probability of 1% in 1 yr

Where g is the gravitational acceleration.

5. Short-term PSHA maps for Alberta



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Peak ground acceleration (PGA as % of g) at a probability of 1% in 1 yr, from 2022 to 2024, for the province of Alberta. The equivalent modified Mercalli intensity scale is included.

Largest seismic hazard estimated south of the Grande Prairie region:

2022: 47% g at a probability of 1% in 1 yr

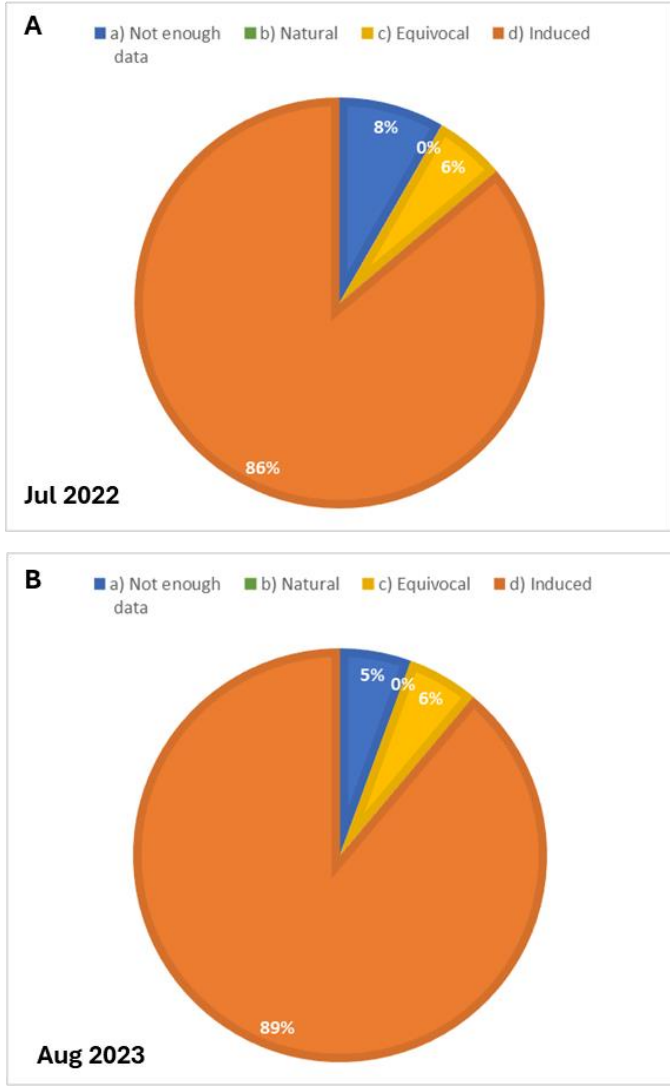
2023: 60% g at a probability of 1% in 1 yr

2024: 50% g at a probability of 1% in 1 yr

Where g is the gravitational acceleration.

6.Discussion

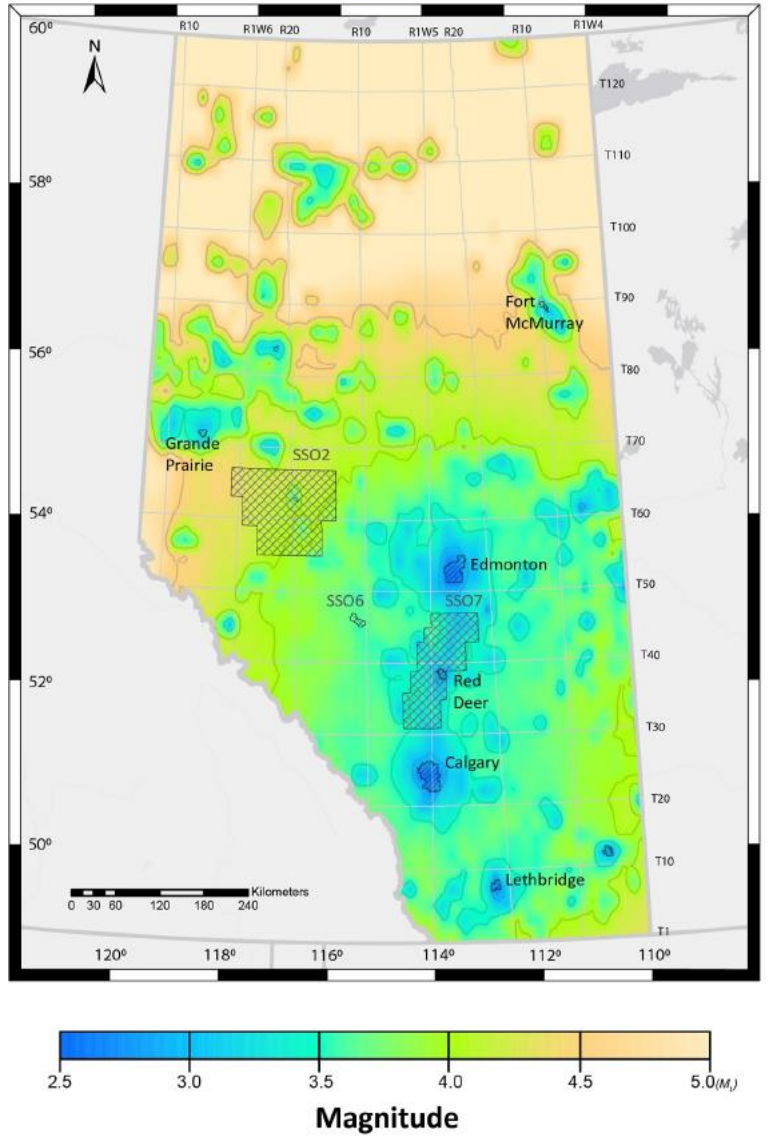
- An update of Directive 065, “Resource Applications for Oil and Gas Reservoirs,” include elements for managing induced seismicity related to disposal operations, including carbon storage.
- Identified seismogenic wells must follow a Monitoring, Mitigation and Response plan.
- How to identify seismogenic wells? Relies on understanding the geology and physical mechanism of fault activation.
- Use of questionnaires as a guide (E.g. Davis and Frohlich, 1993; Verdon et al., 2019; Foulger et al. 2023). They rely on spatio-temporal correlation between seismic sequences and operational activities



Pie chart resulting from answering the questionnaire from Foulger et al. (2023), considering the available data for the Kakwa earthquake sequence up to July 2022 (A) and August 2023 (B)

6.Discussion

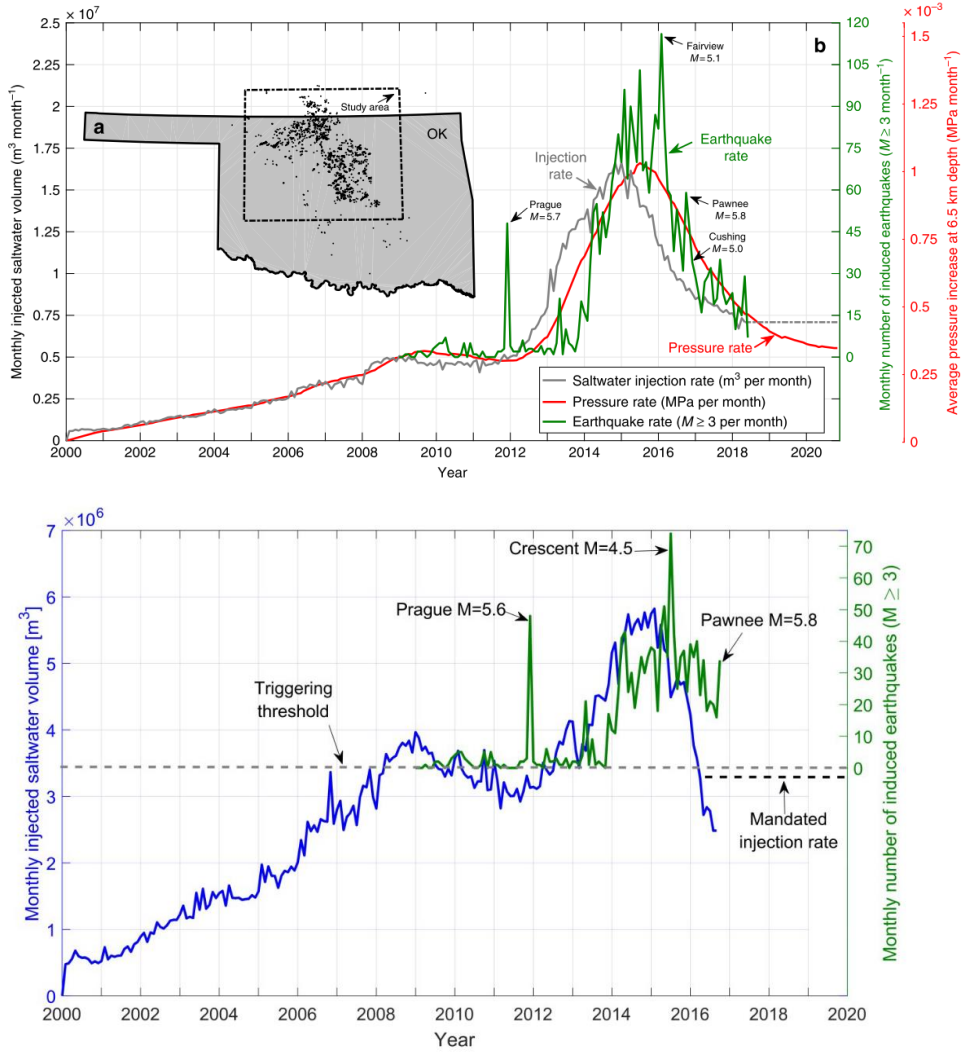
- Mitigation strategies are under a traffic light protocol (TLP), which aims to reduce the magnitude and frequency of induced seismic events.
- Under the TLP, operators must report and actively mitigate if earthquakes pass a certain magnitude (yellow light) and implement drastic mitigation toward fault deactivation after another magnitude threshold (red light).
- Earthquake iso-nuisance and iso-damage maps can help determine the magnitude thresholds in Alberta, considering factors like population distribution and site amplification effects.



Combination map (iso-nuisance and iso-damage) including trailing seismicity factor (long-term operations on the right) and using magnitudes for a tolerance level of 50% probability to cause nuisance to 30,000 households and damage to 3 households.

6.Discussion

- After a red-light event, the aim is to move toward fault deactivation before activities can resume. Thus, considerable operational changes might be necessary to achieve this.
- The point of fault activation refers to the injection (change in stress, or pressure) required to make the fault (or faults) active.
- Estimating the point of fault activation can be done by: an empirical analysis using reservoir engineering information, reservoir engineering modeling, etc.
- Change of operations toward fault deactivation is encouraged during the yellow-light stage.



Evolution of the seismicity and total volume injected in the Arbuckle Fm., Oklahoma. Estimated pressure rate is included. From Langenbruch and Zoback (2016).

Questions?