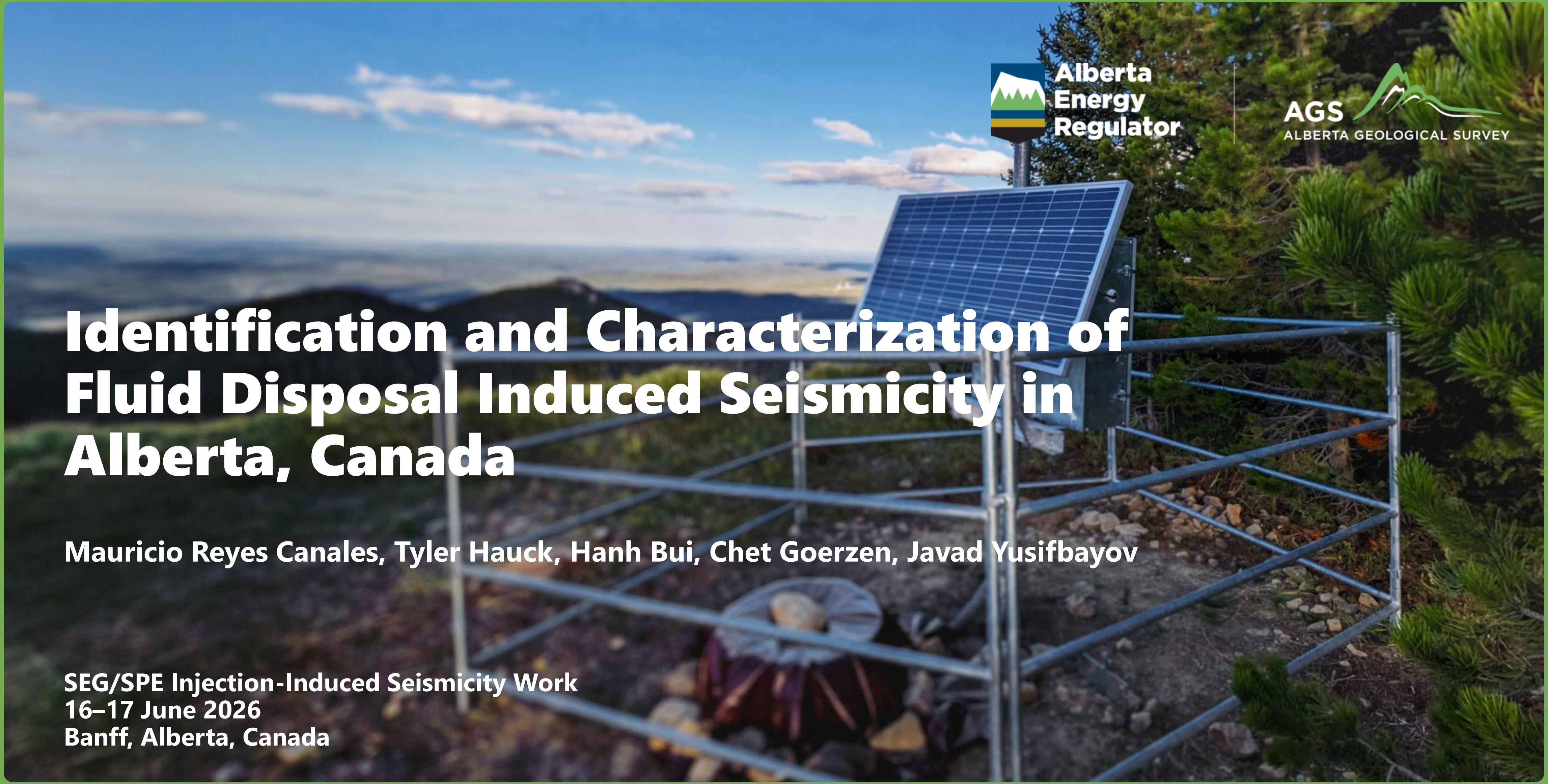


Alberta Energy Regulator

AGS ALBERTA GEOLOGICAL SURVEY

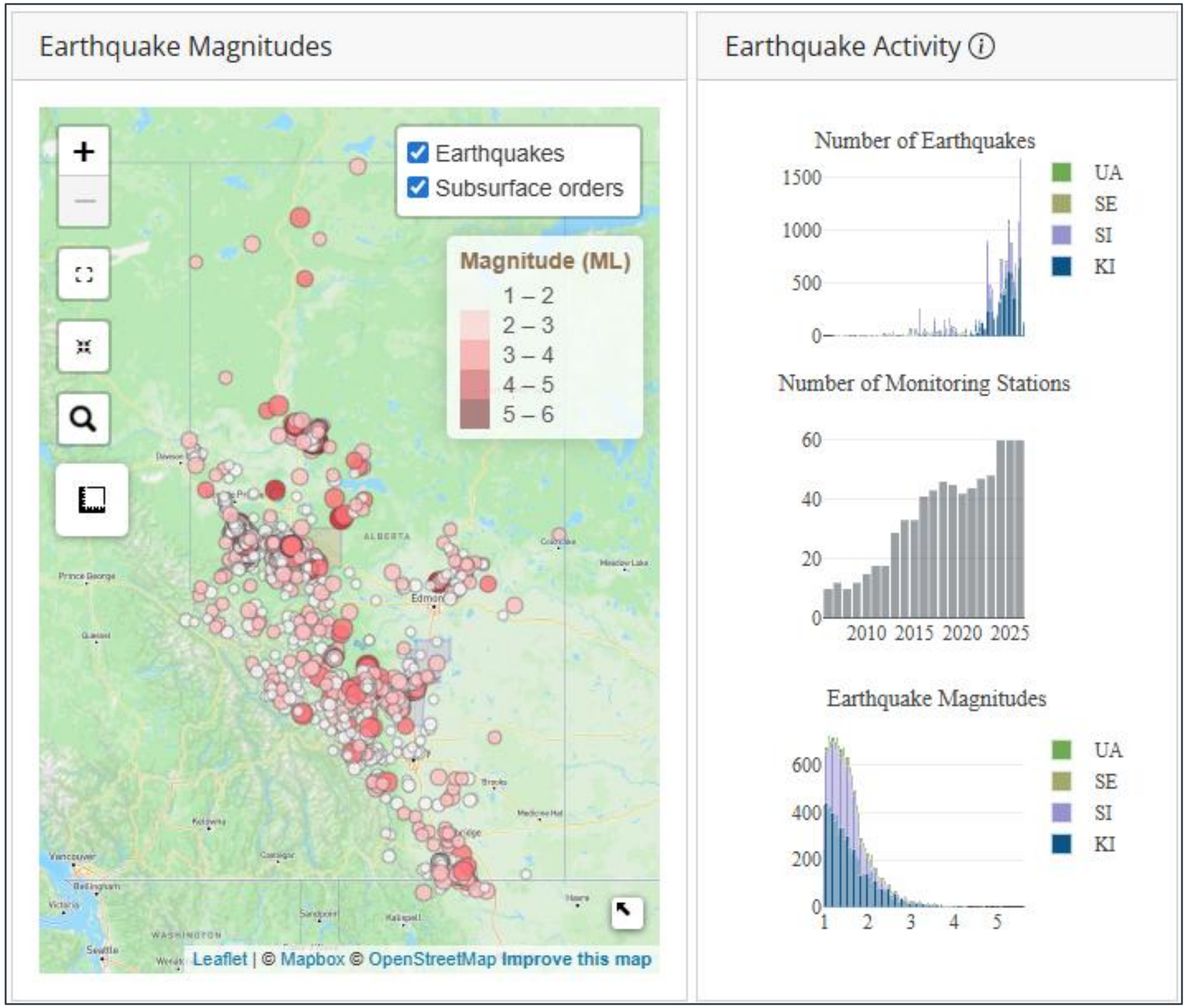
Identification and Characterization of Fluid Disposal Induced Seismicity in Alberta, Canada

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

SEG/SPE Injection-Induced Seismicity Work
16–17 June 2026
Banff, Alberta, Canada

1.Introduction

- Induced seismicity in Alberta has evolved over time: Shift from hydraulic fracturing–dominated to disposal-related seismicity.
- Disposal-induced seismicity can be more difficult to identify, mitigate, and regulate.
- Disposal-induced seismicity has shown the largest induced events in Alberta.
- Alberta now provides a rich set of real-world disposal case studies.
- We aim to outline practical steps to identify disposal-induced seismicity using Alberta examples.



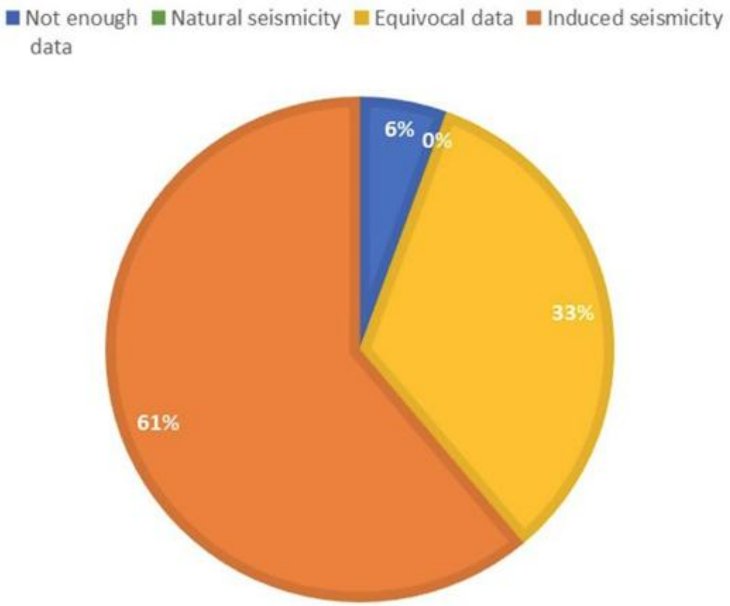
Earthquake locations colored by local magnitude (ML). Time-series plots summarize the number of recorded earthquakes, increase in the seismic monitoring network, and magnitude distribution. From **Alberta Geological Survey Earthquake Dashboard**

2.Identification of Induced Seismicity

- Induced seismicity identification has a degree of uncertainty, especially for disposal.
- Recent tools provide more nuanced ways to represent uncertainty, moving beyond the seminal questionnaire of Davies and Frohlich (1993).
- We use evidence-based frameworks to guide interpretation (Foulger et al., 2023). Spatiotemporal plausibility is the dominant signal.
- Geological context and physical feasibility are essential.

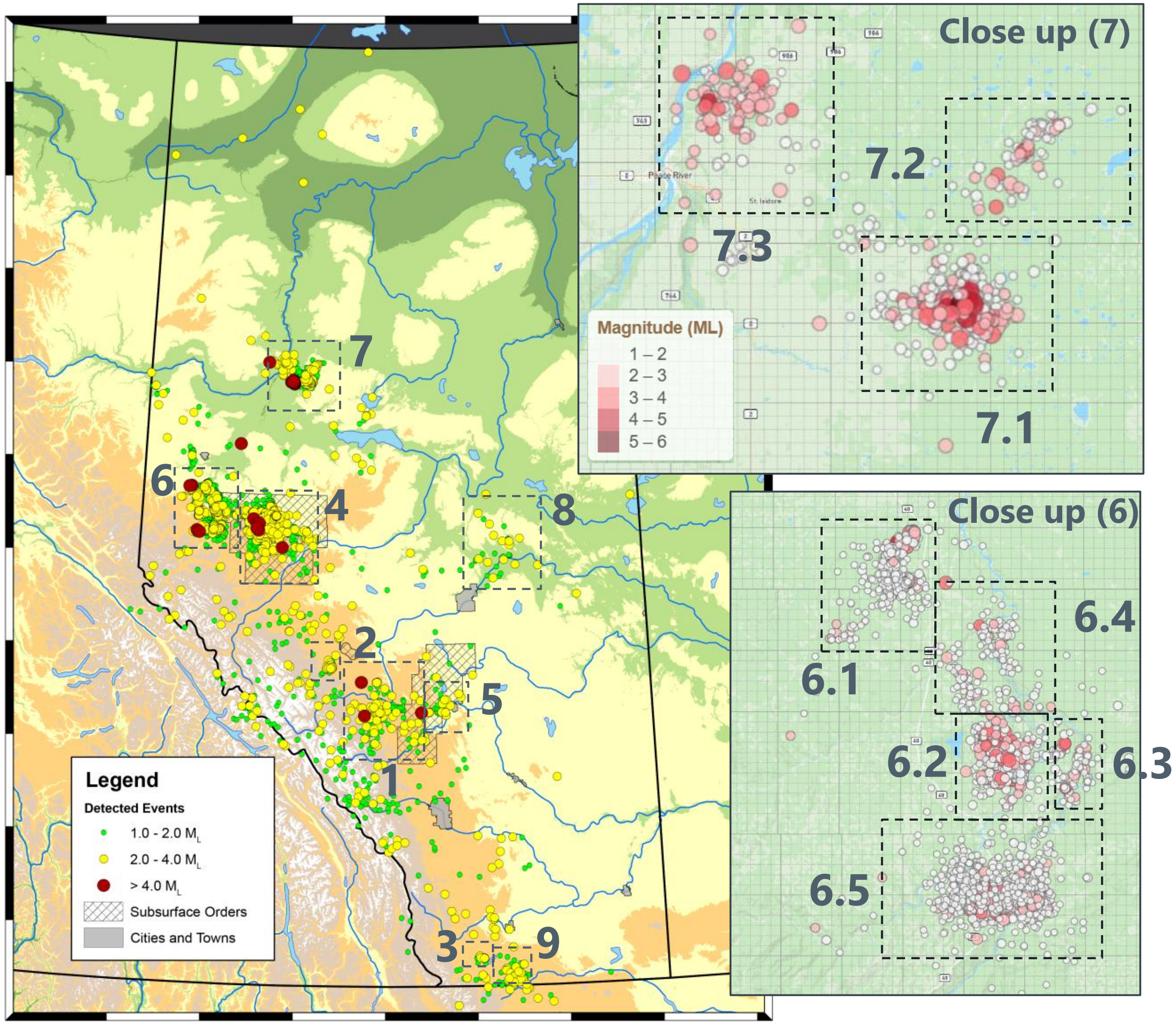
Core questions - Foulger questionnaire

- Temporal Consistency (10 points)
- Epicentral Correlation (100 points)
- Hypocentral Correlation (100 points)
- Temporal Correlation (100 points)
- Pre-industrial seismicity (20 points)
- Focal Mechanism (10 points)
- Other Seismic and non-seismic data (20 points)



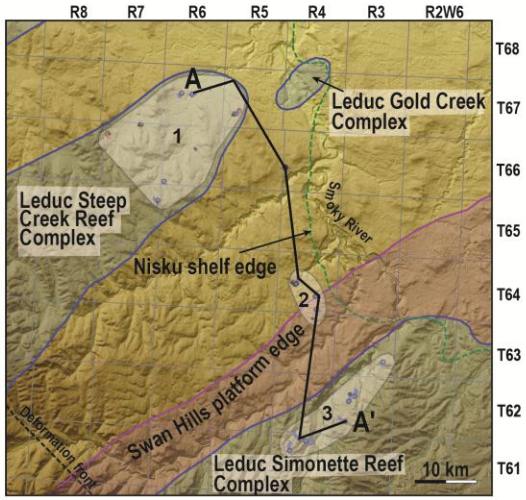
Pie chart generated from all responses to the questionnaire from Foulger et al. (2023) using the available data for the Reno earthquake sequence, northwestern Alberta, up to March 2023. From AGS Open File Report (Reyes Canales et al., 2026).

3. Main seismic clusters in Alberta

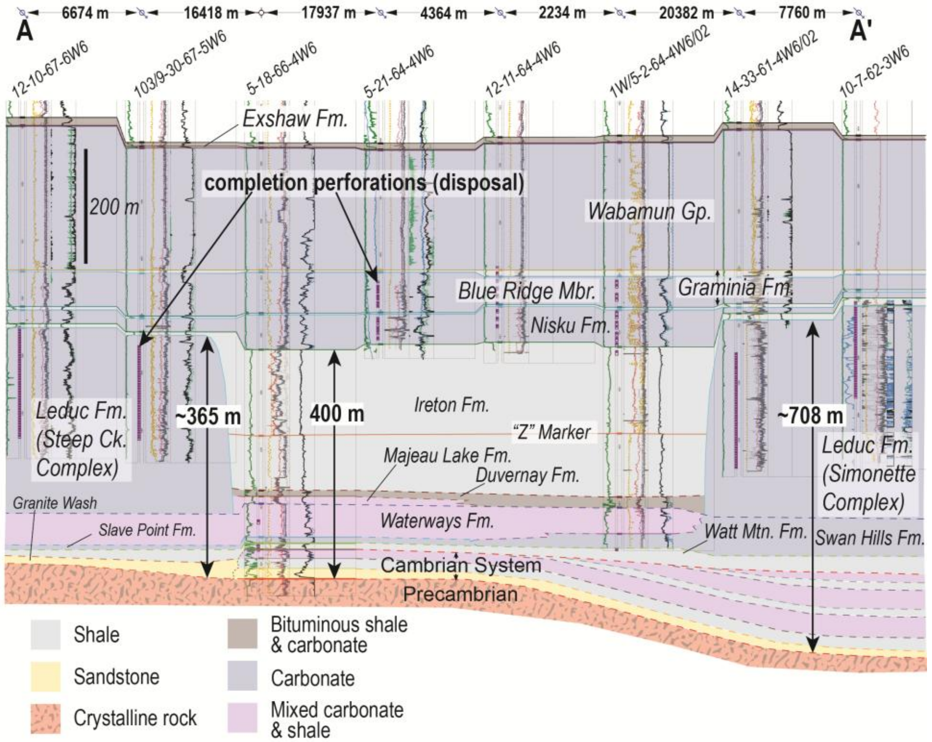


1. Rocky Mountain House (Gas extraction)
2. Cordel Field (**Disposal**)
3. Cardston (HF)
4. Fox Creek (HF)
5. Red Deer (HF)
6. South Grande Prairie cases (**Disposal**):
   - 6.1 Gold Creek
   - 6.2 Central Musreau Lake
   - 6.3 East Musreau Lake
   - 6.4 North Musreau Lake
   - 6.5 Kakwa
7. Peace River region (**Disposal**):
   - 7.1 Reno Cluster
   - 7.2 North Heart
   - 7.3 North Peace River
8. Redwater (Carbon Capture)
9. Milk River (Natural)

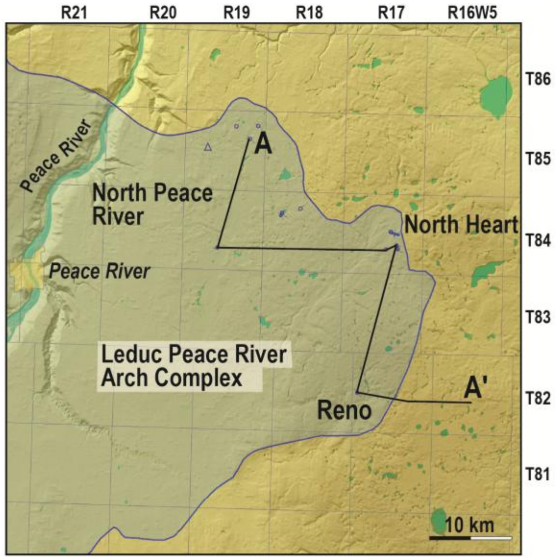
Geological Framework: South Grande Prairie



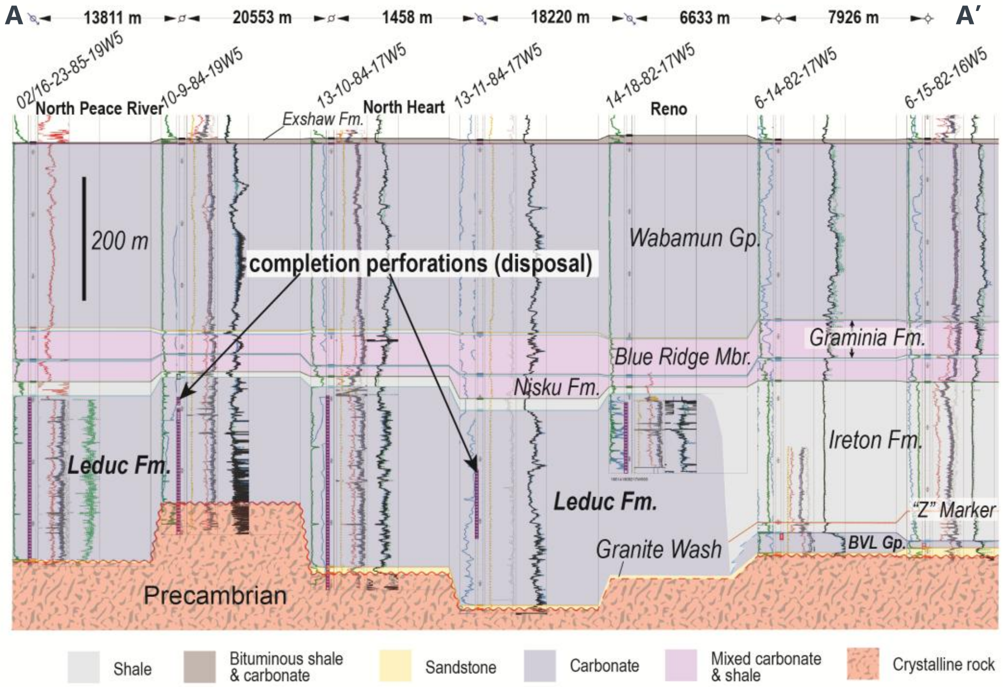
Stratigraphic cross-section (A–A') across the region, showing disposal wells, the Leduc Formation, Winterburn Group and underlying basement.



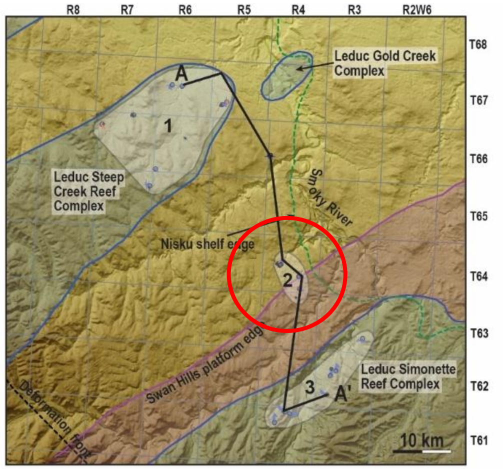
Geological Framework: Peace River region



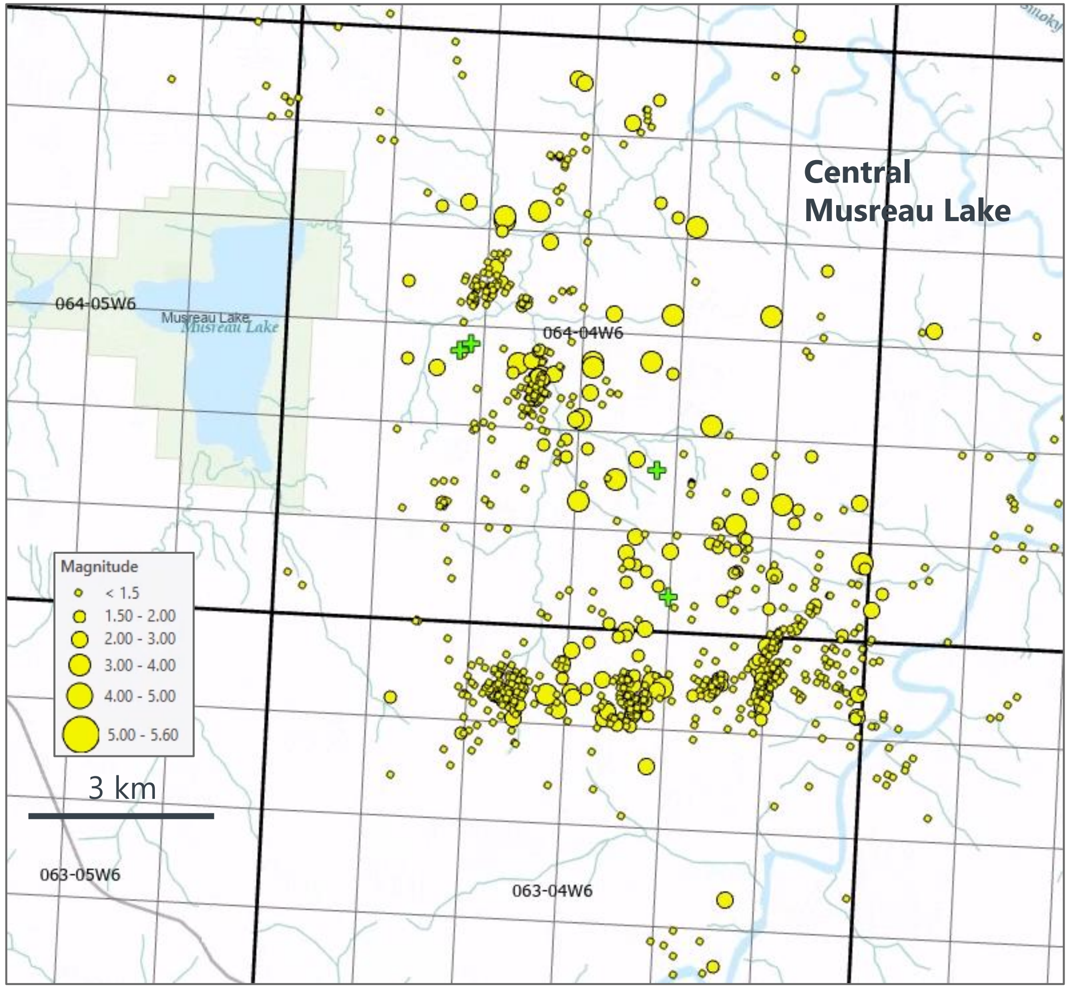
Stratigraphic cross-section (A–A') across the region, showing disposal wells, the Leduc Formation, and underlying basement.



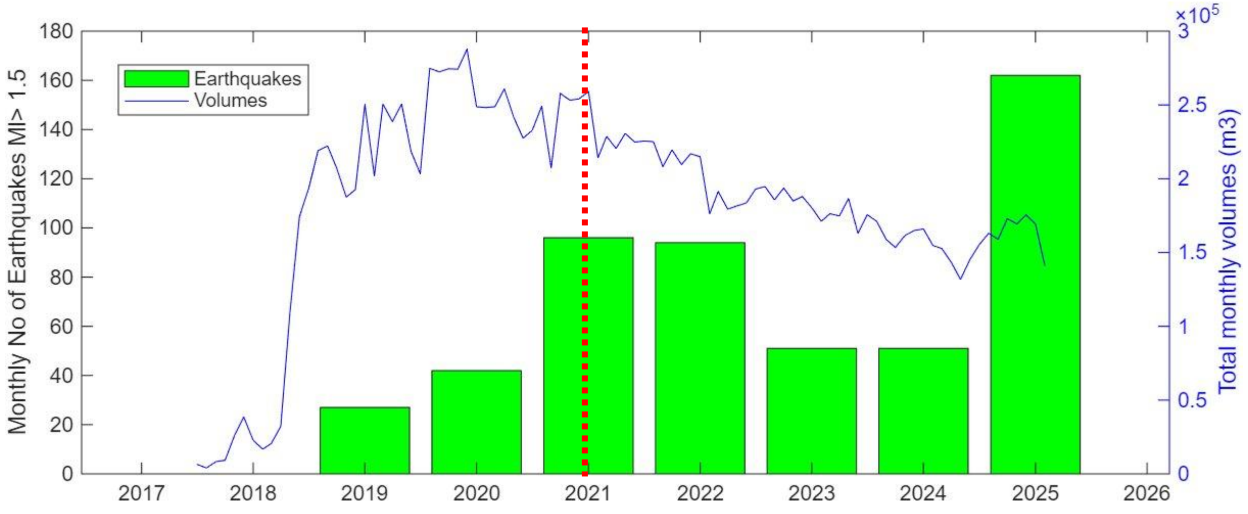
4. Central Musreau Lake cluster



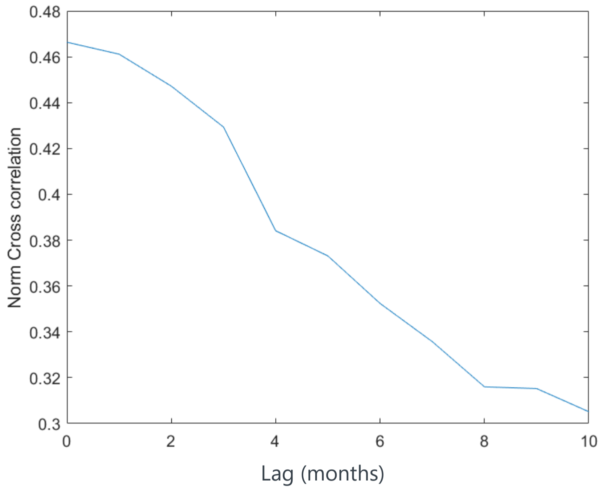
- Seismicity first identified in late 2019, southeast of Musreau Lake.
- First notable event reached ML 3.94 in December 2019.
- Seismicity spatially clustered near water disposal wells, targeting the Winterburn Group (Nisku / Blue Ridge carbonates).
- High seismicity rates observed in 2021-2022. Seismic activity declined in subsequent years with reduced injection volumes.
- Sudden reactivation in 2025, despite lowering volumes.



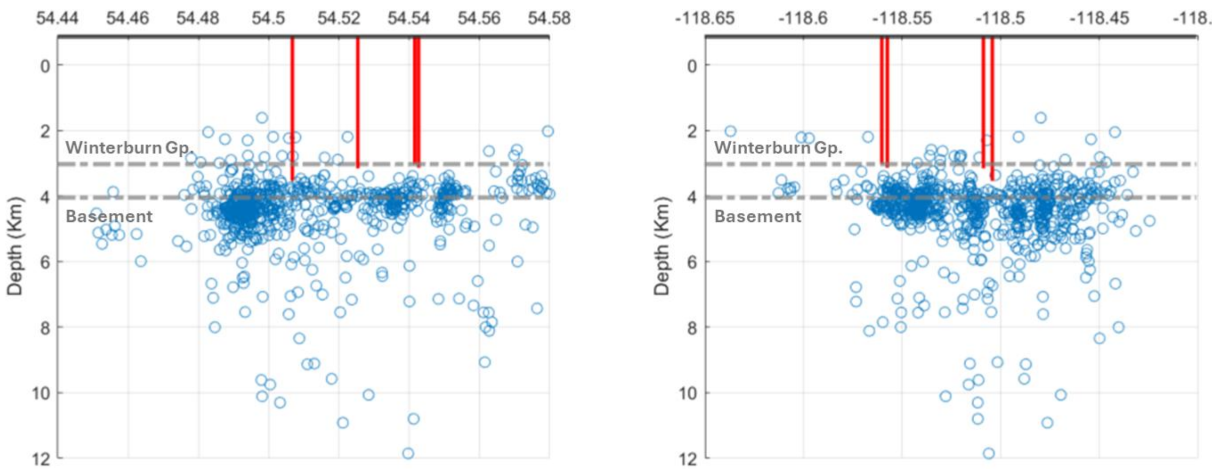
Location map for the Central Musreau Lake clusters. The green cross shows the location of the disposal wells injecting into the Winterburn Group. Figure adapted from a manuscript in preparation for journal submission.



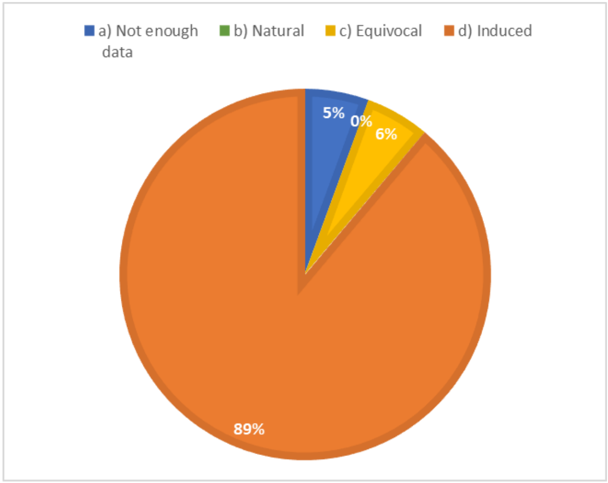
Annual number of earthquakes larger than magnitude ML>1.5 and total monthly injection volumes from the Winterburn disposal wells, Central Musreau Lake cluster



Normalized cross-correlation coefficient as a function of the time lag (months) resulting from cross-correlating seismicity rates and injection rates for the Central Musreau Lake cluster

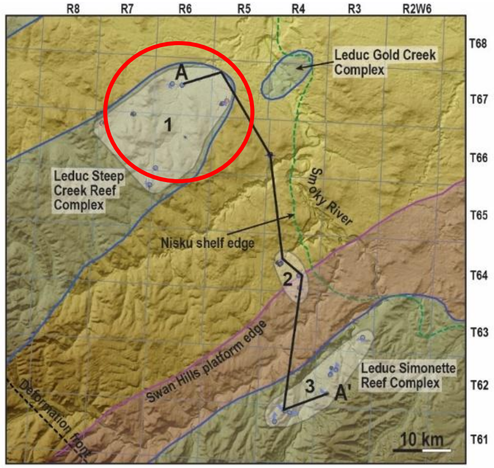


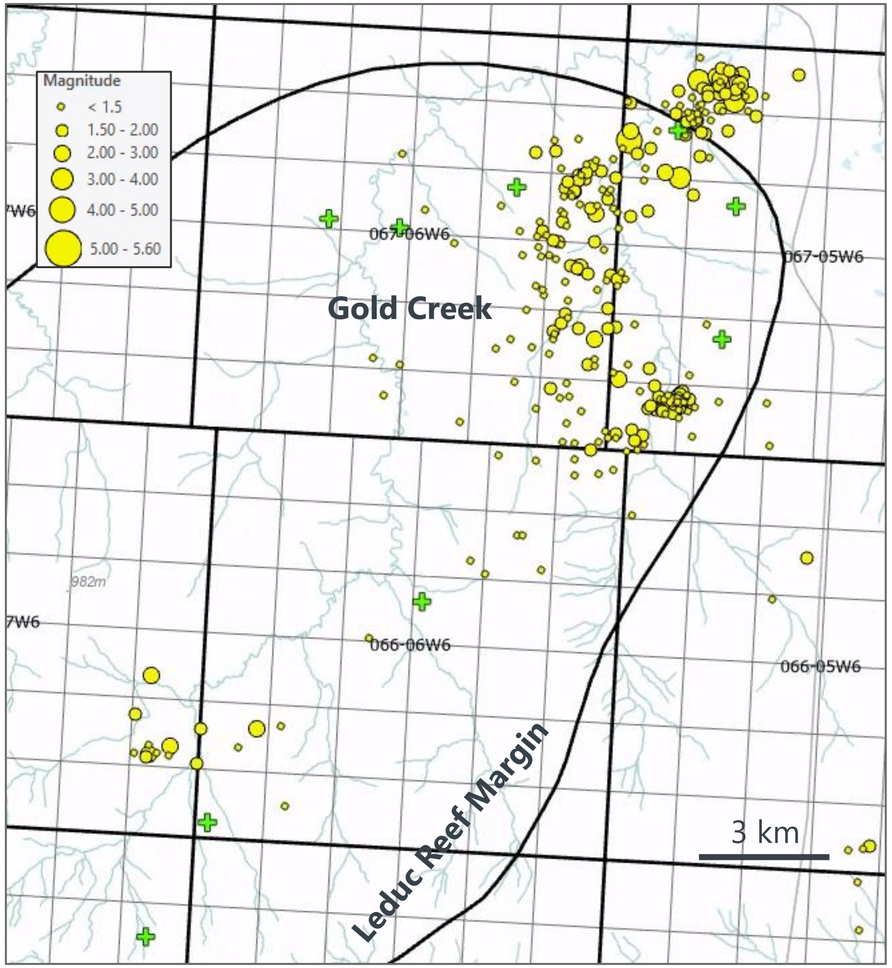
Depth profiles (Left: south-north cross-section; right: west-east cross-section) of the seismicity in the Central Musreau Lake cluster (d). The red vertical lines show the wells injecting into the Winterburn Gp.



Pie chart generated from all responses to the questionnaire from Foulger et al. (2023) using the available data for the Central Musreau Lake cluster. Figures adapted from a manuscript in preparation for journal submission.

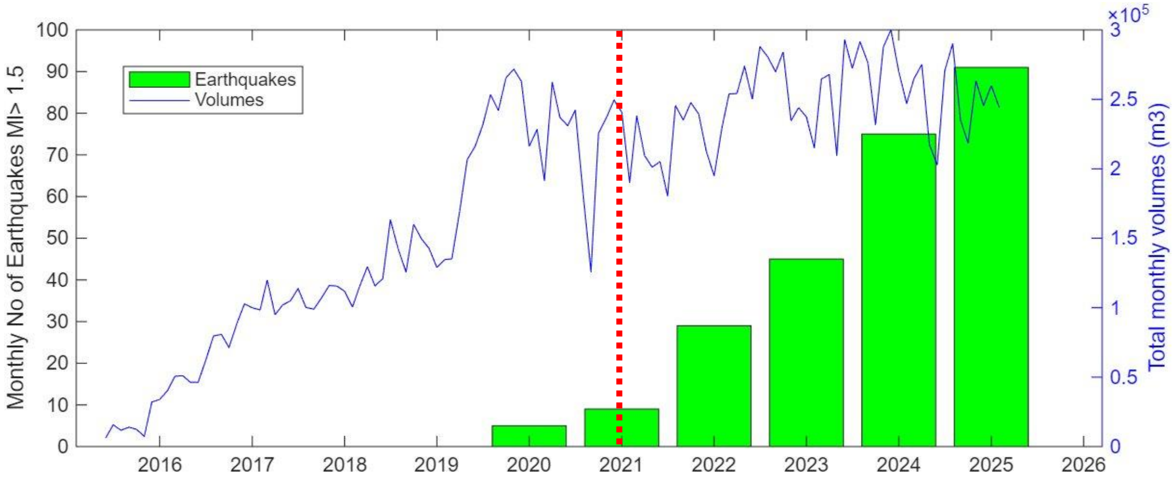
5. Gold Creek cluster



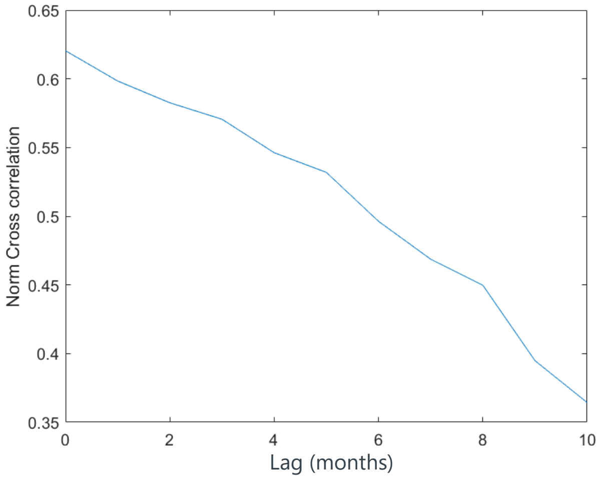


Location map for the Gold Creek cluster. The green cross shows the location of the disposal wells injecting into the Leduc Fm. Figure adapted from a manuscript in preparation for journal submission.

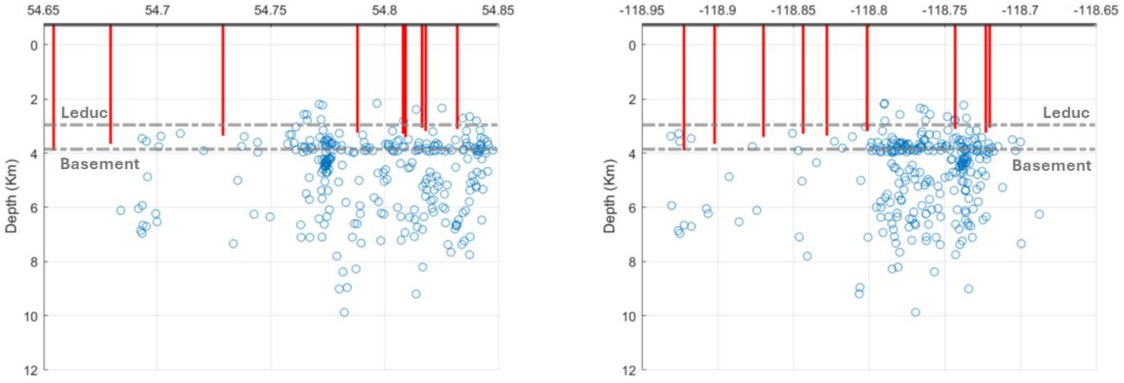
- Seismicity emerged ~4 years after the onset of disposal operations, in late 2020. Earthquake rates have increased rapidly since then.
- Multiple water disposal operations in the Steep Creek Reef (Leduc Fm.)
- Some events have reached M>4, including significant felt earthquakes (largest event M=4.5, Oct 2024).
- Little evidence of comparable seismicity prior to disposal activities.
- Earthquake depths are consistent with basement-involved fault activation.



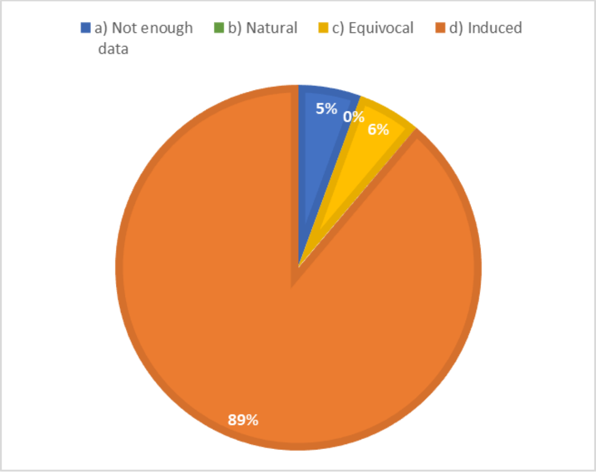
Annual number of earthquakes larger than magnitude ML>1.5 and total monthly injection volumes from the Leduc disposal wells, Gold Creek cluster



Normalized cross-correlation coefficient as a function of the time lag (months) resulting from cross-correlating seismicity rates and injection rates for the Gold Creek cluster

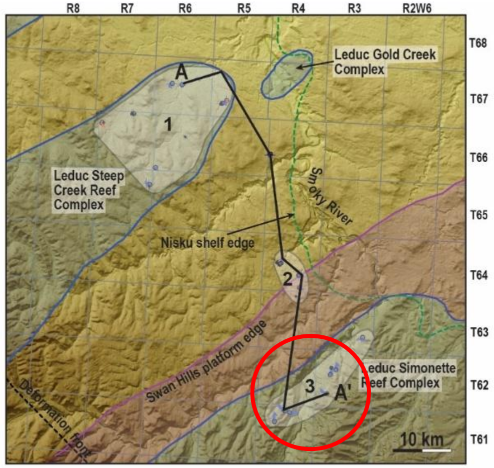


Depth profiles (Left: south-north cross-section; right: west-east cross-section) of the seismicity in the Gold Creek cluster (d). The red vertical lines show the wells injecting into the Leduc Fm.

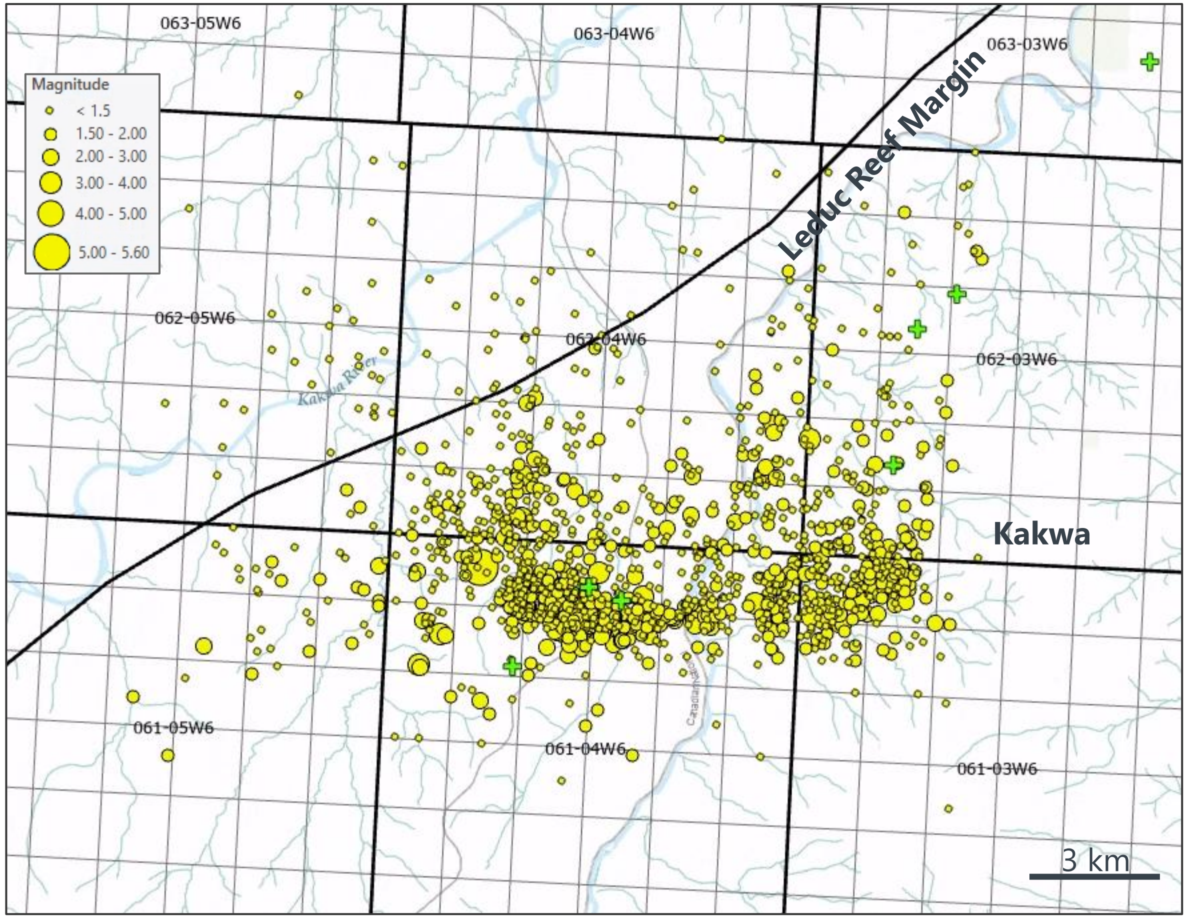


Pie chart generated from all responses to the questionnaire from Foulger et al. (2023) using the available data for the Gold Creek cluster. Figures adapted from a manuscript in preparation for journal submission.

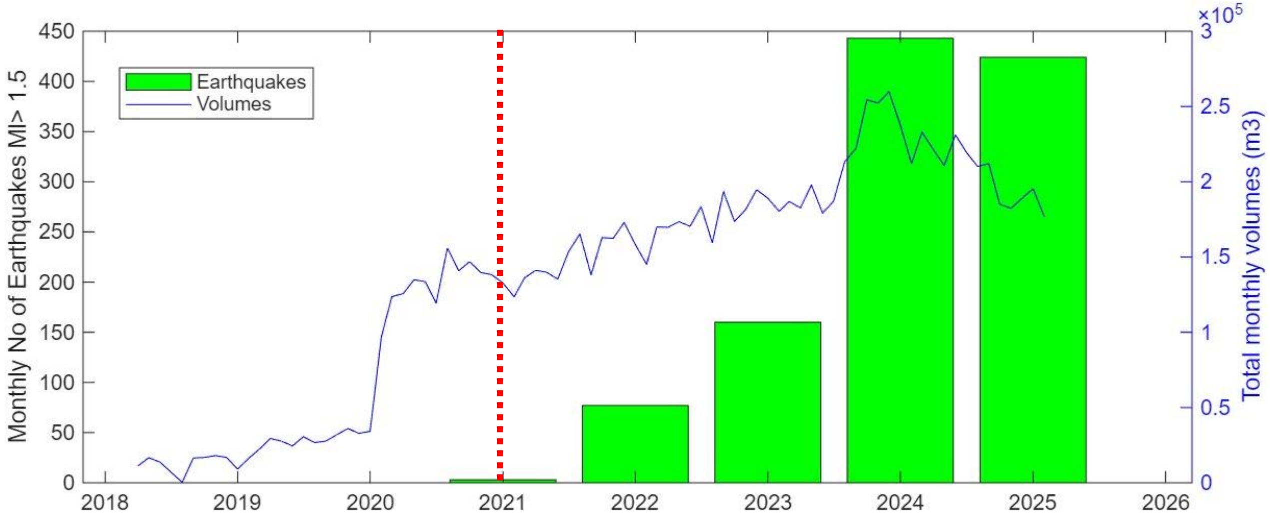
6. Kakwa cluster



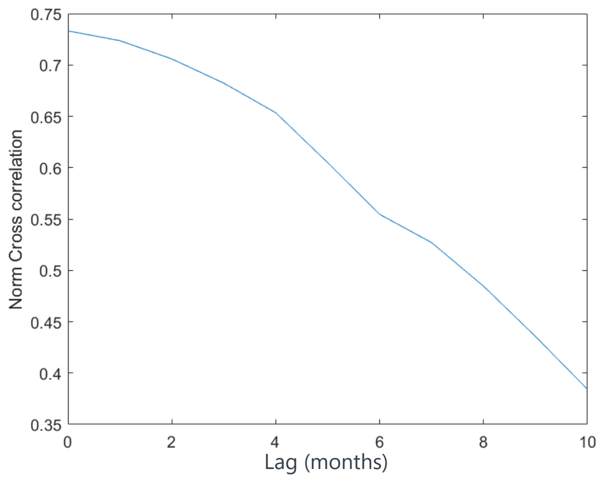
- Seismicity began ~3 years after the onset of disposal operations.
- Multiple high-volume disposal wells inject into the Leduc Formation (Simonette reef complex).
- Multiple events have reached M > 4, including significant felt earthquakes (largest event M=5.1, Feb 2025).
- Kakwa progressed from low-level activity to a sustained seismic sequence.
- Little evidence of comparable localized seismicity prior to disposal operations
- Earthquake depths are consistent with basement-involved fault reactivation.



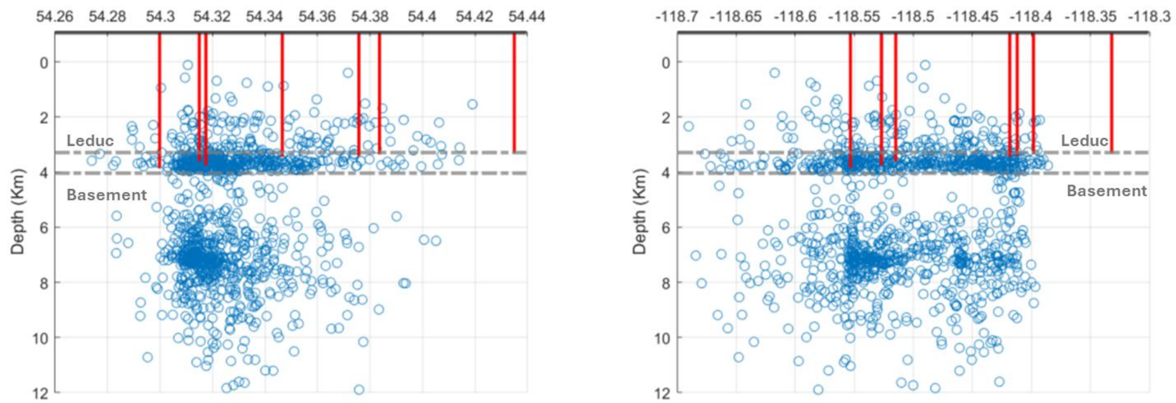
Location map for the Kakwa cluster. The green cross shows the location of the disposal wells injecting into the Leduc Fm. Figure adapted from a manuscript in preparation for journal submission.



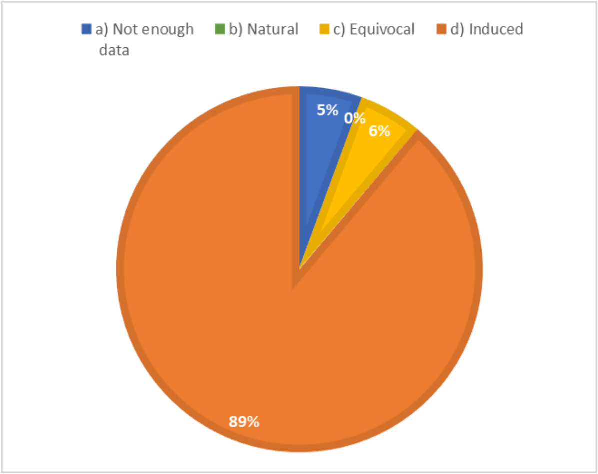
Annual number of earthquakes larger than magnitude ML>1.5 and total monthly injection volumes from the Leduc disposal wells, Kakwa cluster



Normalized cross-correlation coefficient as a function of the time lag (months) resulting from cross-correlating seismicity rates and injection rates for the Kakwa cluster.



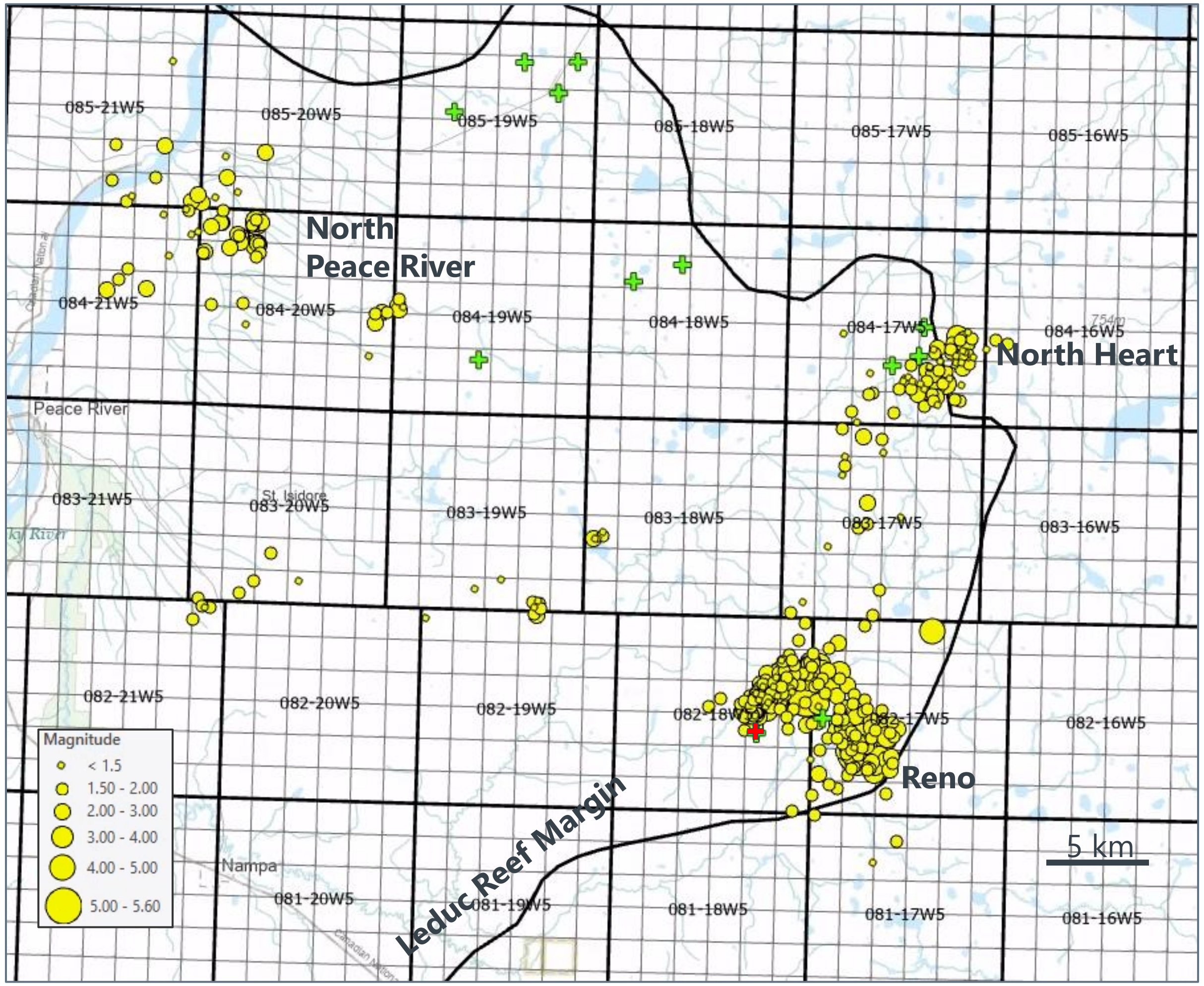
Depth profiles (Left: south-north cross-section; right: west-east cross-section) of the seismicity in the Kakwa cluster (d). The red vertical lines show the wells injecting into the Leduc Fm.



Pie chart generated from all responses to the questionnaire from Foulger et al. (2023) using the available data for the Kakwa cluster. Figures adapted from a manuscript in preparation for journal submission.

7. Peace River clusters

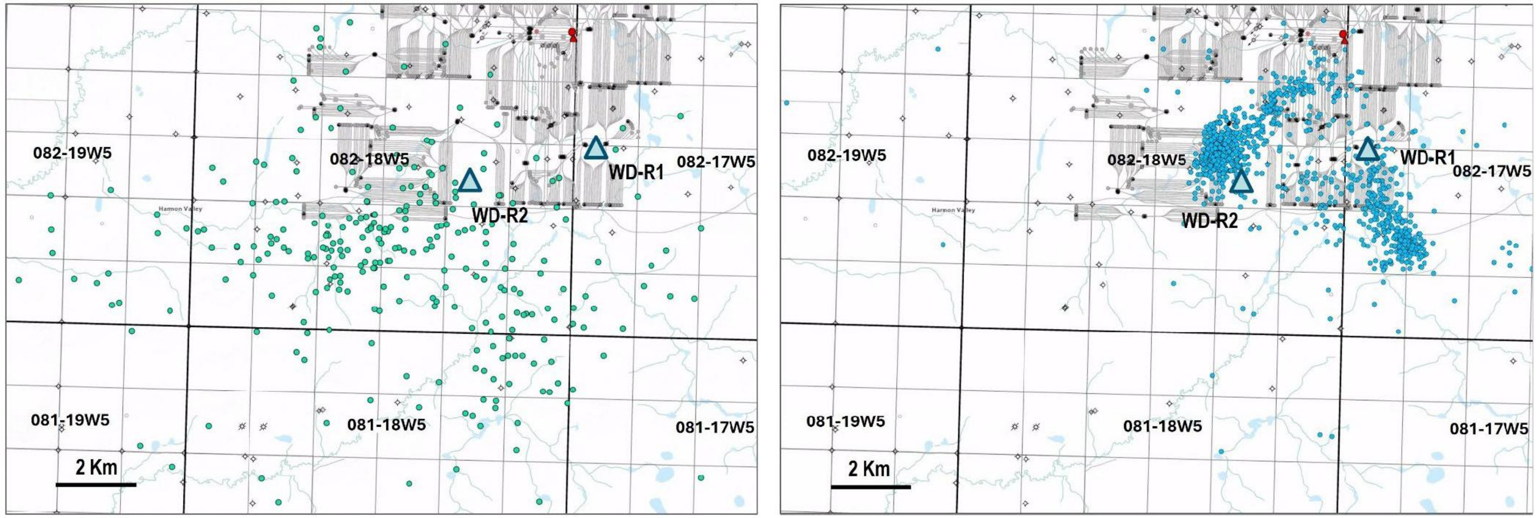
- Three distinct seismic clusters identified in the Peace River region: North Peace River, North Heart, and Reno.
- All clusters are located along the Leduc Fm. reef margin, where the Leduc Fm. locally overlies or is separated by a thin interval from Precambrian basement.
- **North Peace River cluster**: Long-standing, low-rate seismicity. Initially interpreted as natural, now related to disposal activity.
- **North Heart cluster**: Spatially and temporally associated with wastewater disposal into the Leduc Fm. Moderate magnitudes.
- **Reno cluster**: Most active and hazardous cluster in the region. Produced some of Alberta's largest recorded disposal-associated earthquakes (ML 5.59 in 2022; ML 5.09 in 2023).



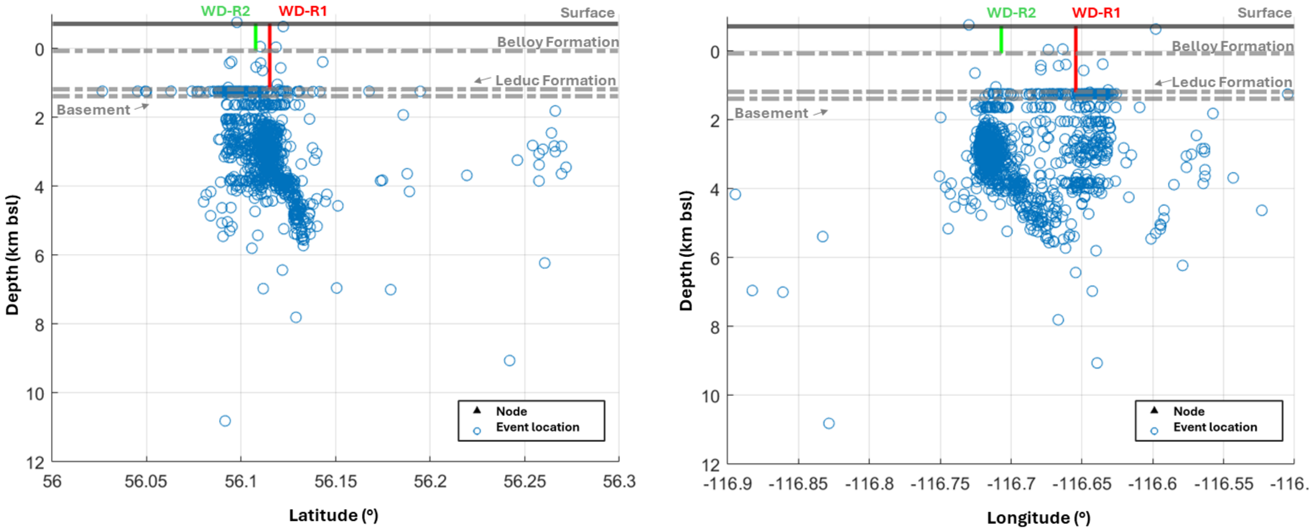
Location map for the seismic clusters in the Peace River region. The green cross shows the location of the disposal wells injecting into the Leduc Fm. Figure adapted from a manuscript in preparation for journal submission.

8. Reno cluster

- Negligible seismicity observed intermittently prior to 2022.
- Rapid escalation of seismicity beginning November 2022, culminating in a M 5.6 event.
- Initial uncertainty regarding seismicity origin due to limited seismic resolution from the regional network
- Presence of multiple industrial activities: Disposal and oil extraction.
- Field deployment of a dense Seismic Nodal Array following the November 2022 mainshock.
- High-resolution nodal data significantly improved earthquake locations and depth constraints.



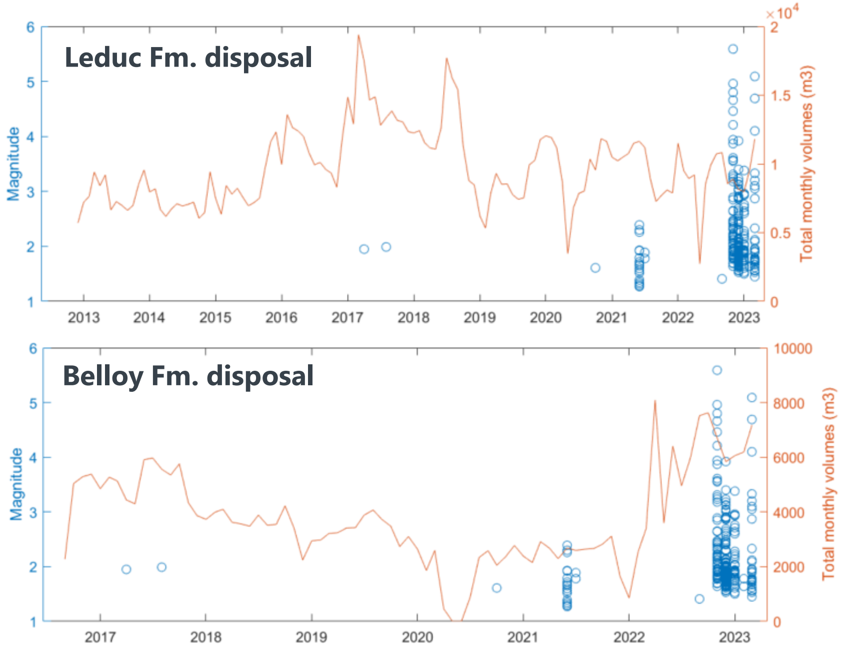
Seismic events in the Reno cluster, recorded by the AGS regional array (left, green dots), data up to March 2023, and local array of seismic nodes deployed by the AGS (right, blue dots), data from December 6, 2022 to January 13, 2023. From AGS Open File Report (Reyes Canales et al., 2026).



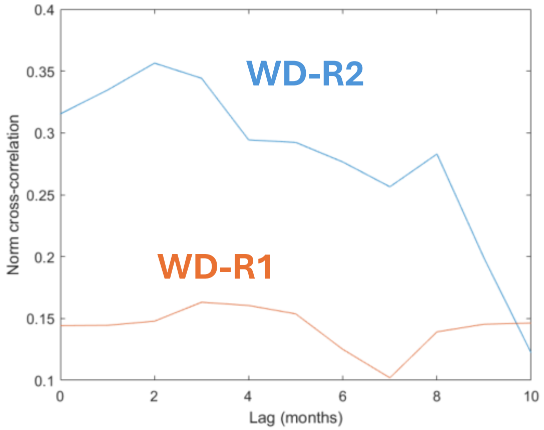
Depth profiles of seismic events in the Reno cluster. Data recorded by the local seismic nodal array. Two disposal wells are in the immediate location of the cluster: WD-R1 injecting into the Leduc Fm., and WD-R2 injecting into the Belloy Fm. From AGS Open File Report (Reyes Canales et al., 2026).

8. Reno cluster

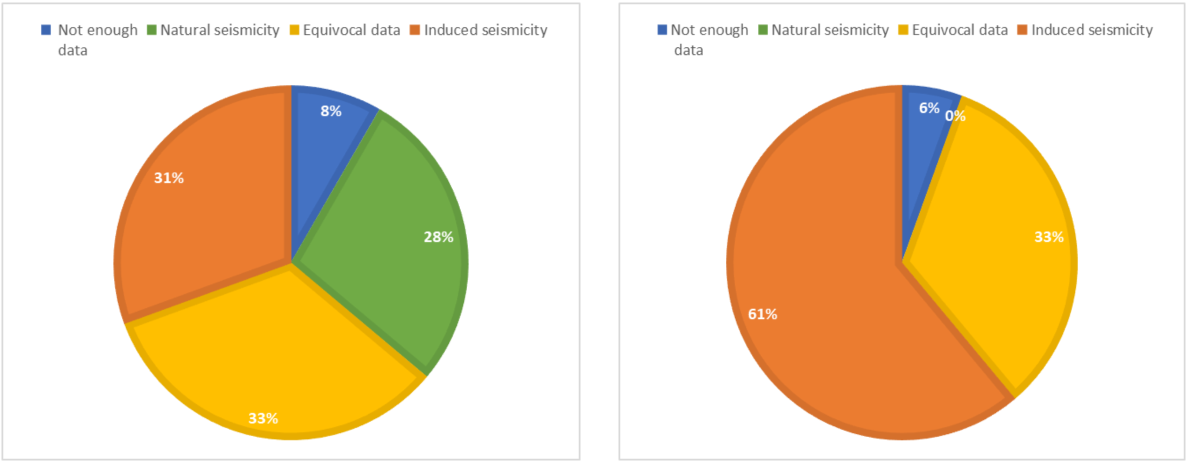
- Seismicity remained active, including a M 5.1 event in March 2023.
- Refined hypocentre depths place seismicity below the sedimentary sequence, consistent with basement-involved fault activation.
- Combined evidence supports an induced seismicity origin.
- Initial assessment (November 2022) showed weak correlation between disposal operations and seismicity.
- Updated questionnaire (March 2023) showed a clear shift toward an induced assessment.



Monthly injection volumes from disposal activity in the Reno cluster and earthquake magnitude vs time.



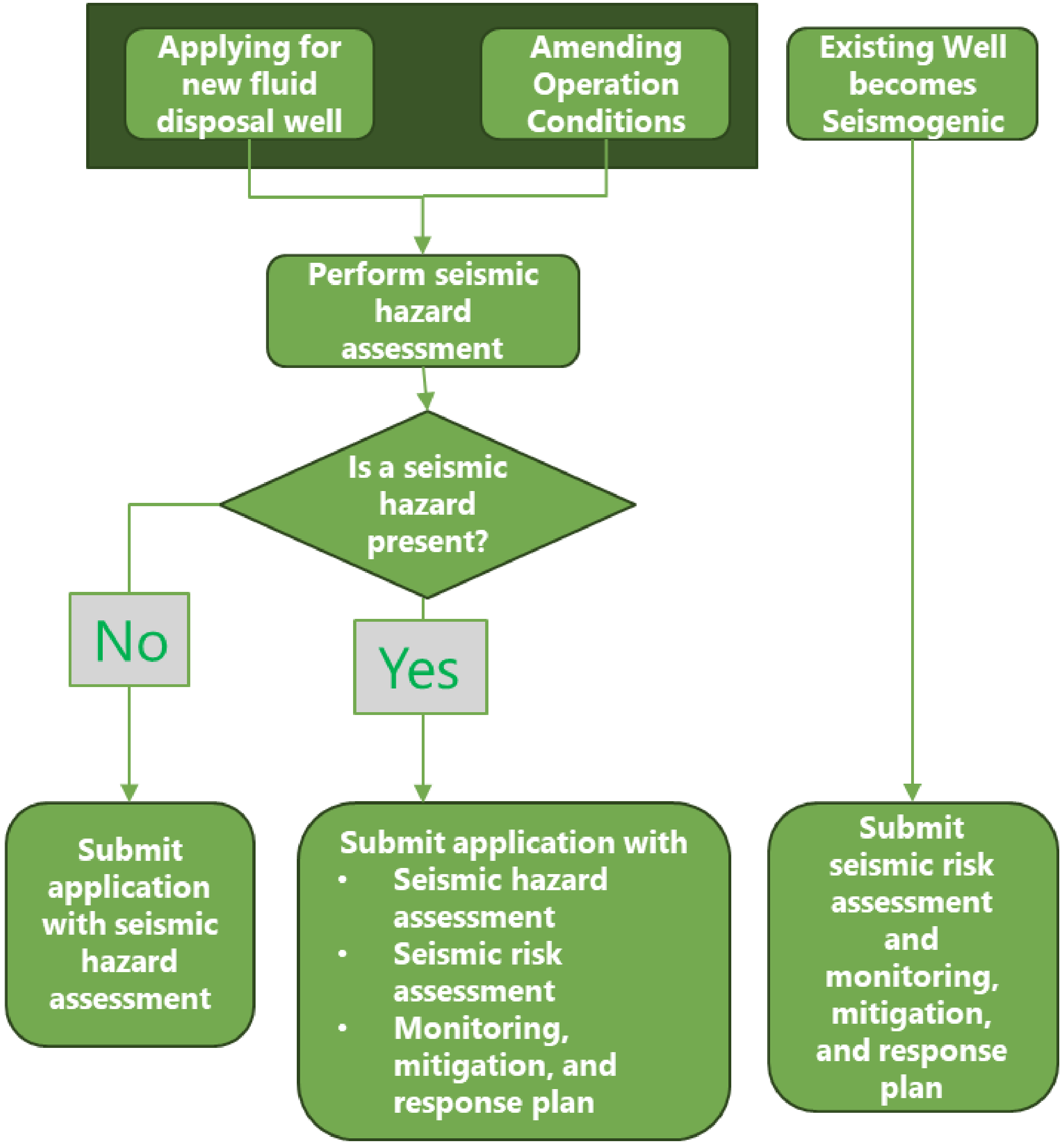
Normalized cross-correlation coefficient as a function of the time lag (months) resulting from cross-correlating seismicity rates and injection rates for the Reno cluster (WD-R1: Leduc disposal; WD-R2: Belloy disposal).

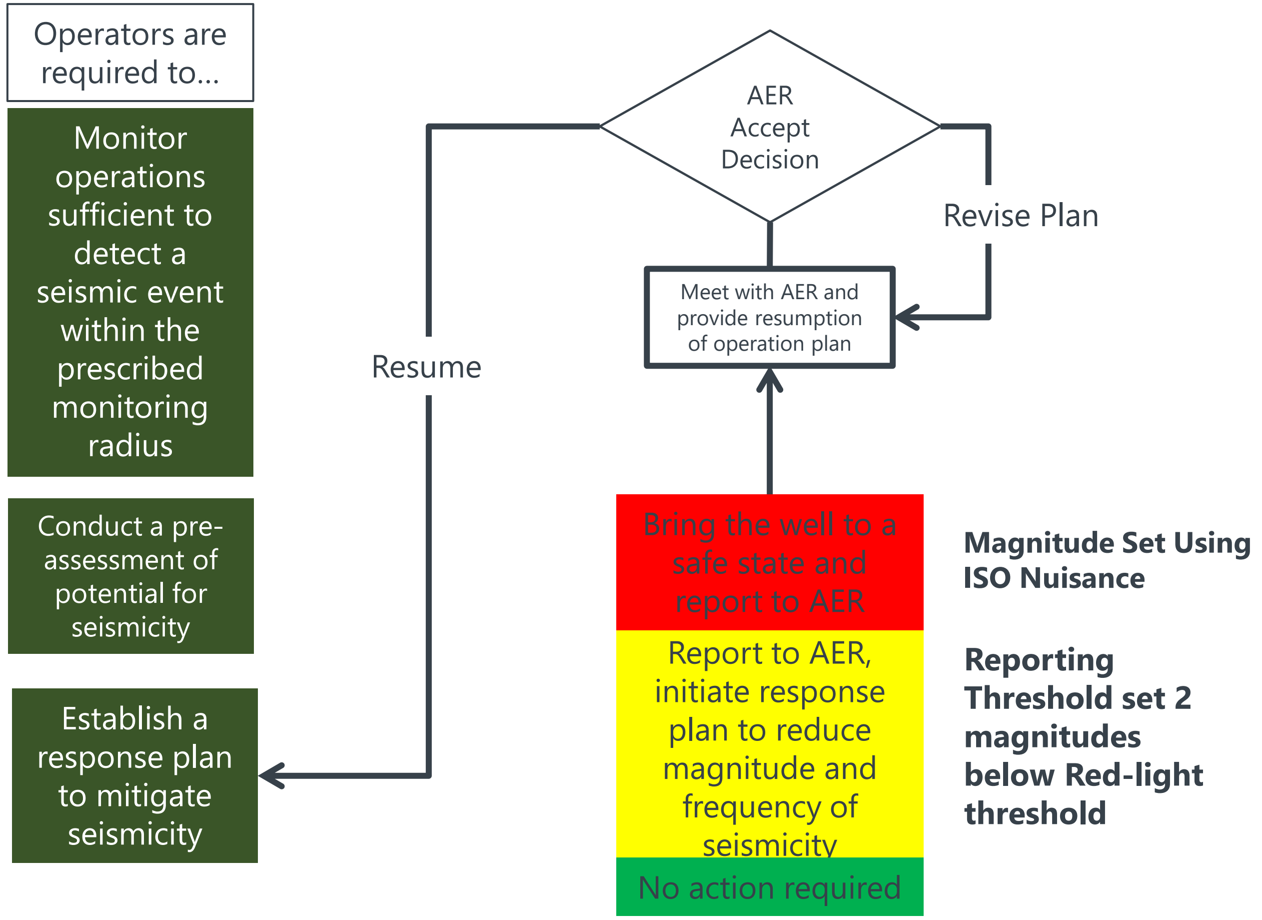


Pie chart generated from all responses to the questionnaire from Foulger et al. (2023) using the available data for the Reno cluster in November 2022 (left) and March 2023 (right).

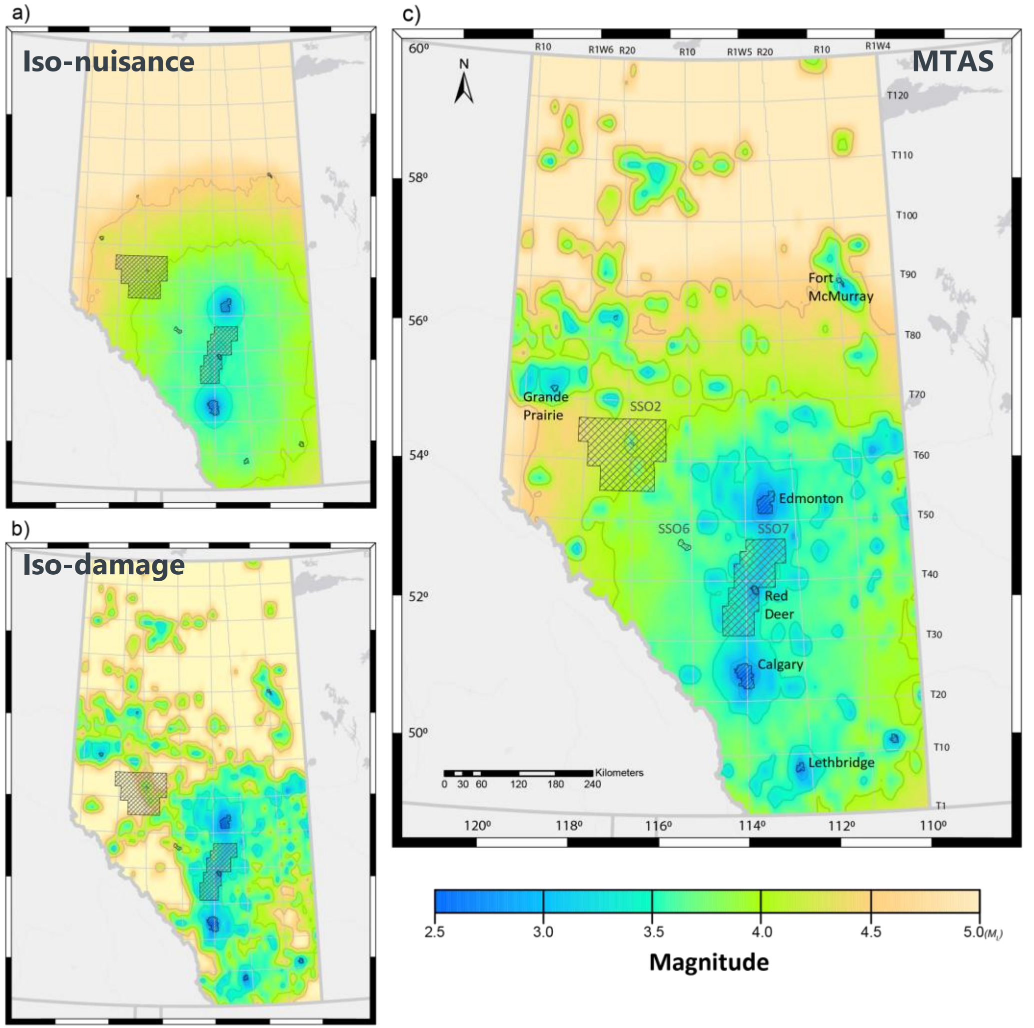
9. Regulatory Approach

- Environmental Protection Orders (EPOs) were issued in response to elevated seismicity: 2021: Musreau Lake, and 2023: Reno. Both EPOs have since been rescinded.
- Directive 065 was modified to address disposal-induced seismicity.
- Induced seismicity assessment prior to approval of new disposal operations.
- MMR (Monitoring, Mitigation and Response) plans and seismic risk assessment for seismogenic wells.
- D065 requires a Traffic Light Protocol (TLP) embedded within the MMR plan (Green / Yellow / Red-light).





Induced seismicity regulatory workflow under Directive 065, showing operator requirements, Traffic Light Protocol (TLP) responses, and AER decision points.



MTAS: Magnitude Threshold for Acceptable Seismicity. 50% probability to cause nuisance to 30,000 households and damage to 3 households, including trailing seismicity for long-term injection activities. From earthquake iso-nuisance and iso-damage mapping in Alberta, [Reyes Canales et al. 2024.]

10. Discussion

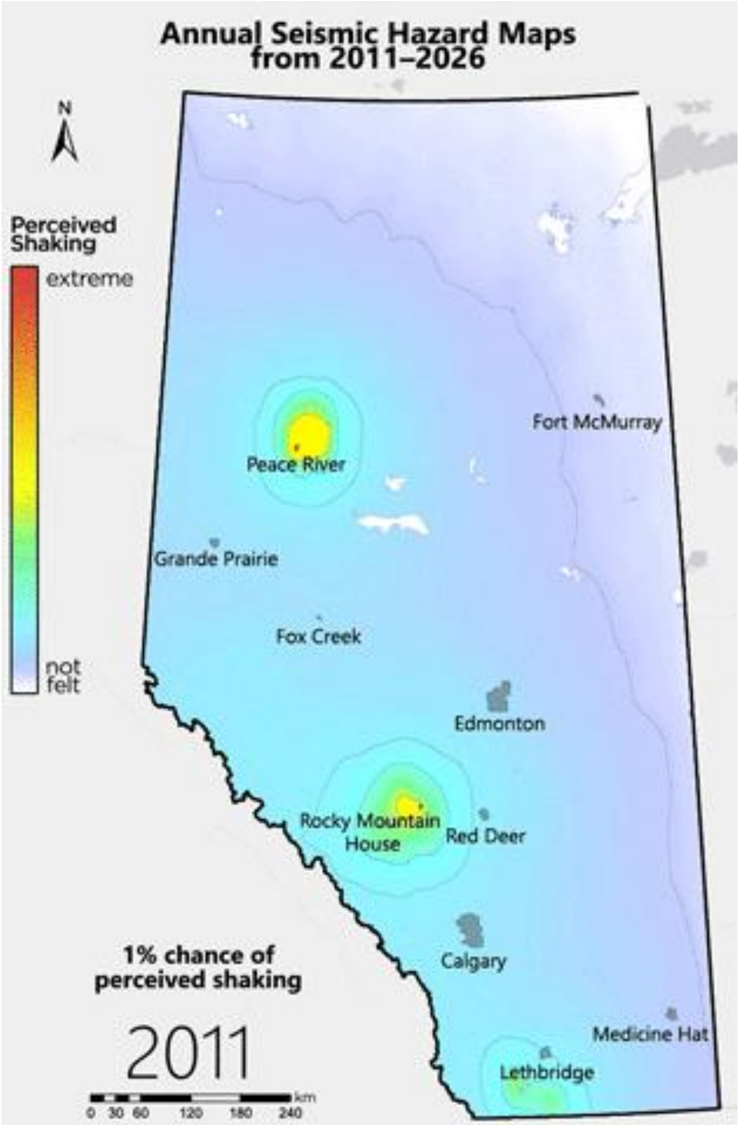
- Basement-involved fault reactivation beneath carbonate disposal targets controls the largest and most hazardous events

- Delayed and cumulative triggering dominates disposal-induced seismicity (years of pressure buildup before rapid escalation).

- Short-term injection–seismicity correlations are often weak or absent and should not be used as the sole attribution criterion.

- Reno illustrates key disposal challenges: years of pressure buildup, and rapid onset of large events.

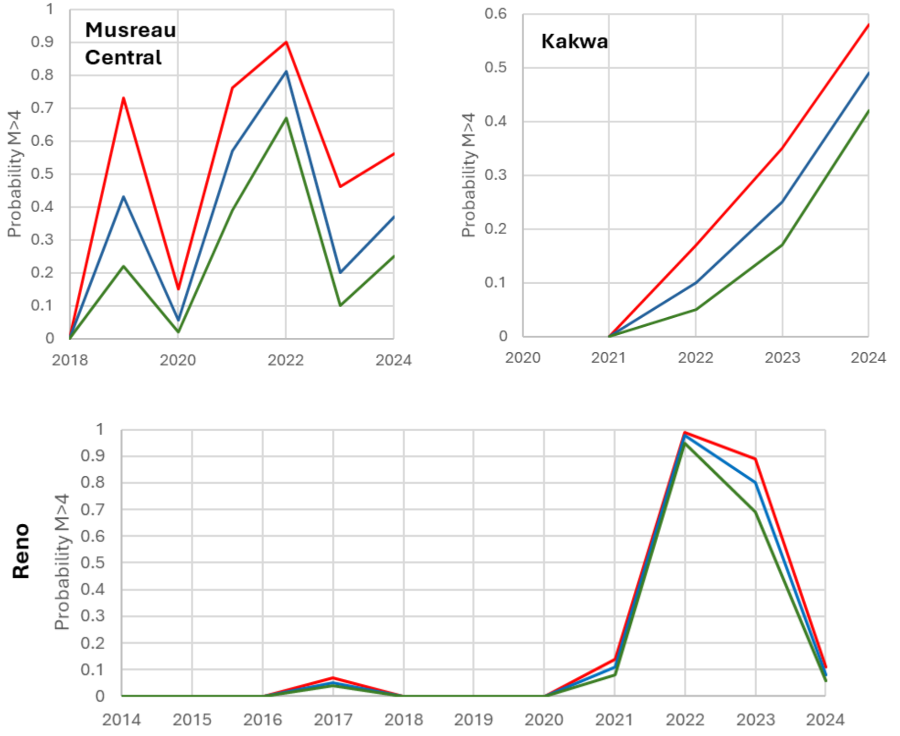
- Questionnaires are effective guides, integrating multiple lines of evidence and enabling transparent communication of uncertainty.



Annual Probabilistic Seismic Hazard Analysis in Alberta, including natural and induced seismic sources. Based on the work from Reyes Canales et al., 2022.

10. Discussion

- Outcome-based regulation must assume uncertainty, multi-operator interaction, and evolving interpretations as new data become available.
- Challenges around mitigation: What is the effectiveness of short-term mitigations?
- Shut-ins may be required to achieve fault deactivation and reduce hazard.
- How to get optimal operation while managing the seismic hazard? What forecasting outputs can guide?



Annual probability of earthquakes larger than M>4 for the Musreau Lake Central, Kakwa and Reno seismic clusters. The green, blue, and red lines represent the upper, central, and lower scenarios, respectively.

See related AGS posters for additional details and case studies:

Real-time seismic monitoring in Alberta: Network expansion, magnitude consistency, and detection thresholds, **Javad Yusifbayov**

High-resolution nodal seismic catalogs for improved subsurface interpretation in the Peace River region, Northwestern Alberta, **Hanh Bui**

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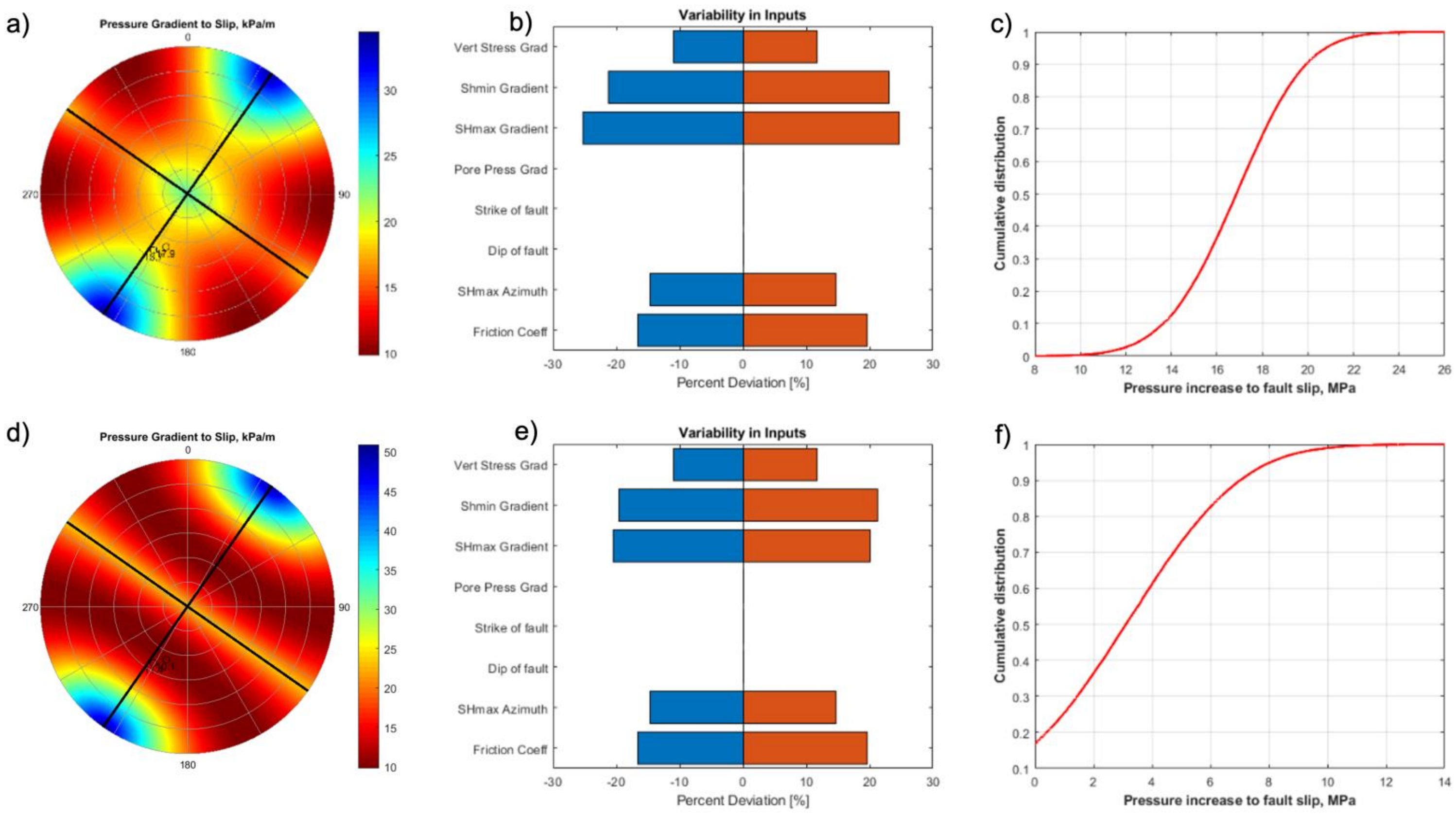
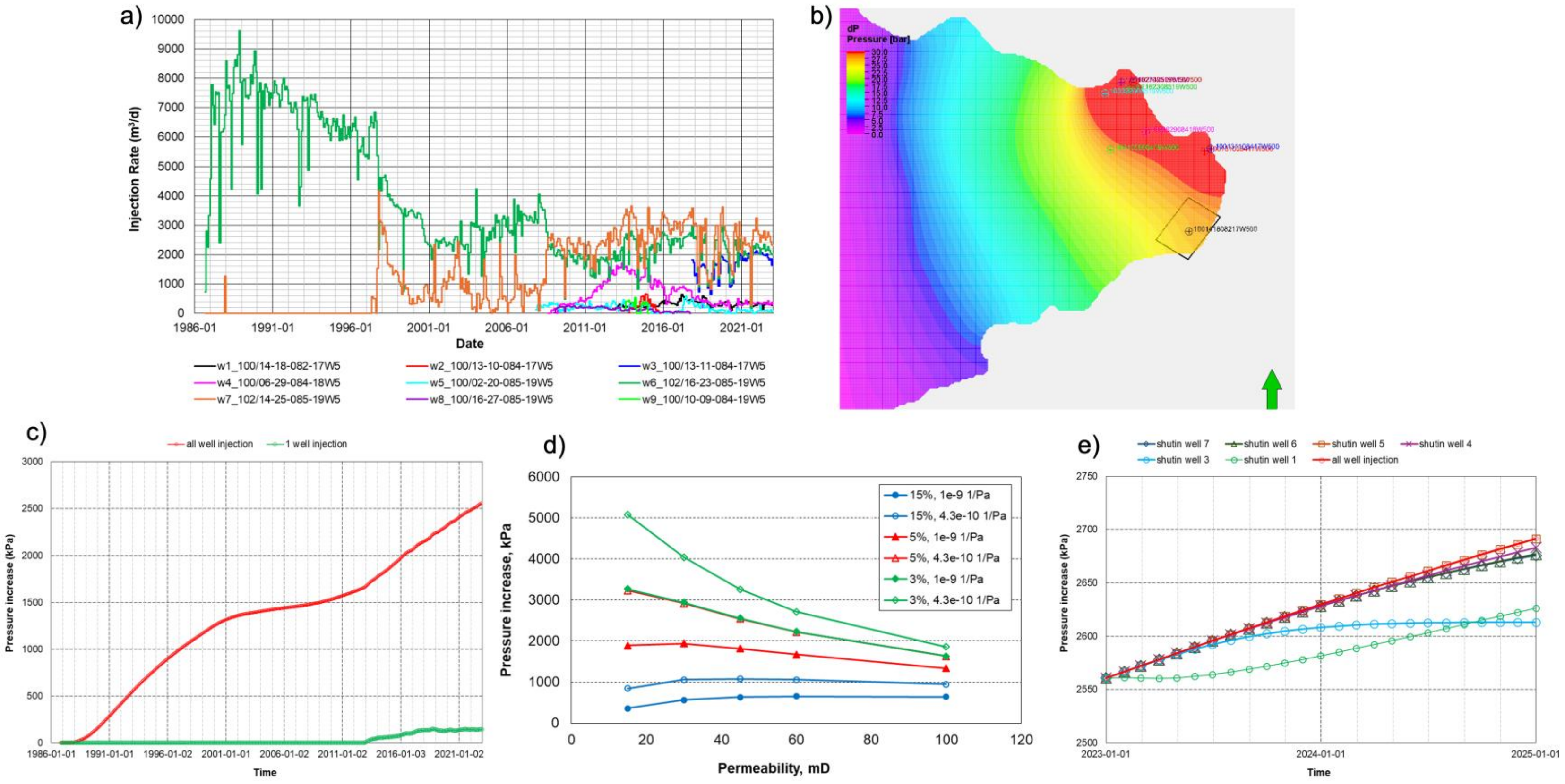
Supplementary Material



Calculated pore pressure gradient required for fault reactivation under the assumed stress state for (a) the Leduc Formation and (b) the Precambrian basement. Black circles denote the interpreted fault orientation (strike N301°E, dip 40°). Black lines represent the principal horizontal stress directions, with SHmax oriented at N35°E. The uncertainty ranges and Monte Carlo–derived cumulative probability distributions of pressure increases required to trigger slip on the interpreted fault under the stress conditions of the Leduc Fm. in (b) and (c), and the Precambrian basement in (e) and (f). Figure adapted from a manuscript in preparation for journal submission.

Supplementary Material



(a) Observed and modeled injection rates for individual Leduc disposal wells during 1989–2022. (b) Model predicted pressure distribution in November 2022, with the interpreted fault indicated by a black triangle dipping Northeast. (c) Model predicted pressure increase history at the location where the fault intersects the Leduc base, showing all well injections (red) and the nearest well injection only (green). (d) Sensitivity of the induced pressure increase at the fault location to formation porosity, permeability, and compressibility. (e) Estimated pressure response at the fault location when each active well is shut in from the end of 2022 for two years, while remaining active wells continue injection at late-2022 rates. Figure adapted from a manuscript in preparation for journal submission.