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# Induced or Natural? Assessing the North Peace River Seismic Cluster Using Nodal Array Data, Regional Catalog, and Questionnaire Inputs

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## Summary

Seismic nodal arrays are increasingly used in local-scale seismic studies for their rapid, cost-effective deployment and ability to provide high-resolution event locations that enhance understanding of seismic clusters. In this study, we use results from nodal array processing such as event locations, magnitudes, and source mechanisms together with regional earthquake catalogs and industrial operations data to evaluate the origin of seismicity in the north Peace River region, northwestern Alberta.

Over a three-month deployment, the nodal array detected 340 events, with the largest event having a local magnitude of 2.83. Among these, 29 events had local magnitudes greater than or equal to 1, and 13 of these events were not detected by the regional seismic array. Despite limited spatial coverage with only seven nodes, event locations show good agreement with those recorded by the regional array. The primary depth distribution of the nodal array events is between 4 and 6 km below the ground surface, suggesting that the events occurred in the Precambrian basement. Additionally, the nodal array identified a small seismic cluster within 15 km of disposal wells, previously undetected by the regional array. This highlights the improved local resolution of event locations provided by the nodal array, which is critical for assessing induced seismicity.

To further evaluate the North Peace River seismic cluster, we used nodal array data together with regional earthquake catalogs and industrial operations information in the application of the Foulger et al. (2023) questionnaire, which emphasizes spatio-temporal correlations with industrial activity. We also performed correlation analysis between annual seismicity rates from the regional catalog and injection volumes, revealing a strong temporal association that persists across multi-year lags. Questionnaire results indicate 61% of points support an induced origin, 28% are equivocal, 11% insufficient, and 0% natural. These findings demonstrate that nodal arrays significantly enhance detection and interpretation of local seismicity, providing valuable input for identifying and characterizing induced seismicity.

## Introduction

Based on data from the Regional Alberta Observatory for Earthquake Studies Network (RAVEN), three seismic clusters have been identified in the Peace River region: Reno, North Heart, and North Peace River. The Reno cluster produced Alberta's largest recorded earthquake, with a local magnitude ($M_L$) of 5.59 in November 2022, linked to nearby disposal operations in the Leduc Formation (Schultz et al., 2023; Vasyura-Bathke et al., 2023; Samsonov et al., 2024). The North Heart cluster has exhibited seismicity since 2016, with preliminary studies suggesting a connection to water disposal into the Leduc Formation (Reyes Canales et al., 2022). The North Peace River cluster is the oldest, with activity recorded as early as 1998. Initially considered natural due to the highly faulted nature and tectonic setting of the Peace River Arch (Cant and O'Connell, 1988), recent research suggests this cluster may also represent disposal-induced

seismicity (Schultz et al., 2023). Following the successful nodal array deployment for the Reno earthquake sequence in 2022 (Reyes Canales et al., 2025), we deployed seven three-component nodal geophones in three rounds between July and November 2023 to investigate the origin of the North Peace River sequence. The deployment provided approximately 200 gigabytes of high-quality seismic waveform data for processing. The main goal was to improve event location resolution, a critical step in assessing induced seismicity. Combined with the regional earthquake catalog and industrial operations data, we applied the Foulger et al. (2023) questionnaire as a guide to evaluate induced seismicity.

## Methods

*Seismic Nodal Data Processing Workflow*

Raw waveform data were first retrieved from the nodal stations and preprocessed to remove linear trends and improve the signal-to-noise ratio. Potential seismic events were then detected using the STA/LTA algorithm (Trnkoczy, 1999), which calculates the ratio of short-term (STA) and long-term (LTA) average signal amplitudes within their respective windows and triggers an event when this ratio exceeds a defined threshold. Following event classification, P- and S-wave arrivals were picked and manually reviewed for timing accuracy. Hypocenter locations were determined using NonLinLoc with the oct-tree importance sampling algorithm (Lomax et al., 2000, 2014). This method accelerates grid searches by recursively subdividing high-probability cells, producing a location probability density function, with the optimal hypocenter corresponding to the minimum misfit point. Local magnitudes were calculated using Yenier's (2017) regionally calibrated formula for the Western Canada Sedimentary Basin, and results were compiled into an event catalog including event origin time, hypocenter location, and magnitude for subsequent analysis. Finally, moment tensor inversion was applied to characterize source mechanisms using the amplitude-based method (Eyre and van der Baan, 2017), which incorporates both P- and S-wave amplitudes to better constrain the inversion results.

*Questionnaire Tool to Evaluate Proposals of Induced Seismicity*

Questionnaire frameworks, first introduced by Davis and Frohlich (1993) and later refined by Verdon et al. (2019) and Foulger et al. (2023), are widely used as a guide to evaluate induced seismicity. These refinements address limitations of the original criteria, particularly when data are incomplete or ambiguous, and provide a structured framework for distinguishing natural from induced events. They have been applied in Alberta, including the Reno cluster in Peace River (Salvage et al., 2023; Reyes Canales et al., 2025). In this study, we applied the Foulger et al. (2023) questionnaire to assess the North Peace River cluster using nodal array data, regional seismic catalogs (Alberta Earthquake Dashboard; Alberta Geological Survey, 2025), industrial operations data, and geological data. This method consists of nine weighted questions, each with four possible responses: (a) insufficient information, (b) evidence supporting a natural origin, (c) inconclusive information, or (d) evidence supporting an induced origin. The questionnaire offers guidance, but each case is unique and may deviate from standard patterns, especially when strong spatio-temporal correlations and clear links between industrial activity and seismicity exist.

## Results

Figure 1 shows detection results from three nodal array deployments. A total of 340 seismic events were detected, with activity recorded almost daily and a peak of 16 events on August 8, 2023. No events were recorded between October 5 and 12, 2023, due to a deployment gap.

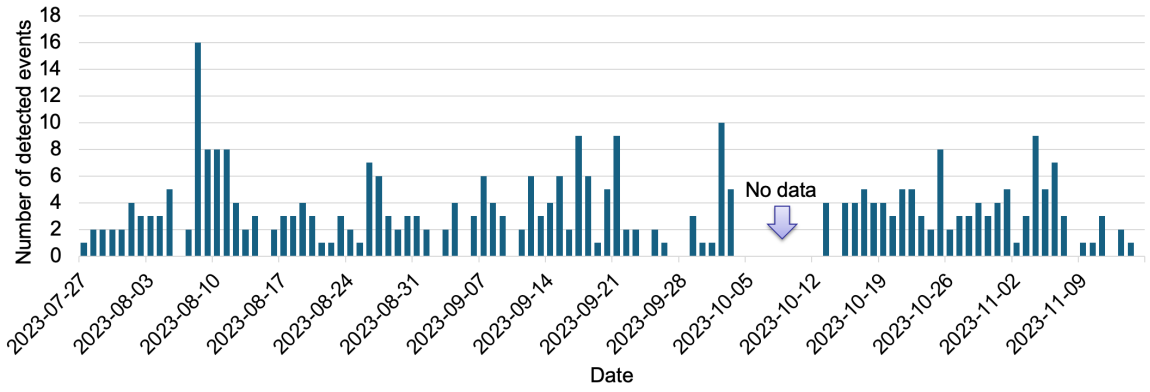



Figure 1. STA/LTA event detection results from three nodal array deployments.

Using P- and S-wave picks and the Peace River 1D velocity model, we located 340 seismic events from three nodal array deployments with NonLinLoc (Lomax et al., 2000, 2014). Figure 2a-c shows map and depth views of all detected events (blue open circles), plotted alongside events located using the regional array (gray open circles) in the Peace River region, together with 13 disposal wells located in proximity (15–25 km) to the seismicity, including wells 1–7 injecting into the Leduc Formation at depths of 1600–1800 m and wells 8–13 injecting into a shallower formation at depths of 500–700 m.

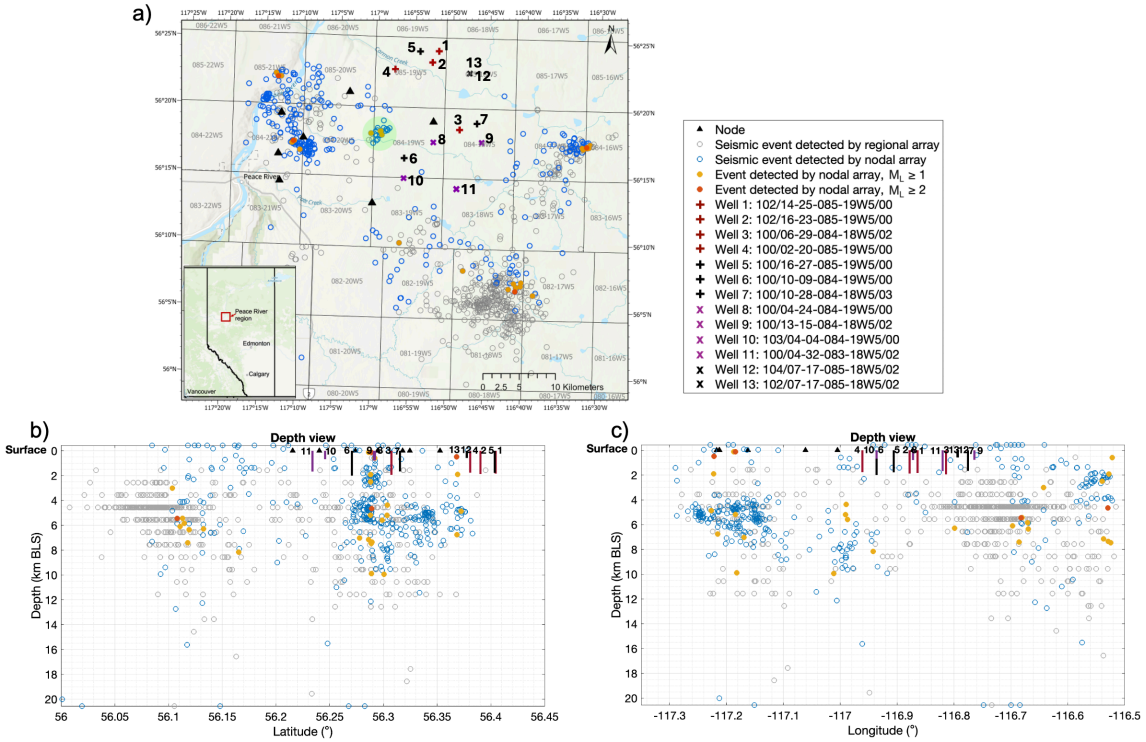



Figure 2. (a) Map view and (b), (c) depth views of events detected by the nodal array (blue circles), plotted together with node locations (black triangles), disposal wells in proximity (labeled with numbers; red "+" and purple "×" symbols indicating active disposal into the Leduc and shallow formations, respectively, and black "+" and "×" symbols indicating suspended status), and seismicity located by the regional array (gray circles). The filled green circle in (a) highlights a small event cluster not detected by the regional array.

Overall, the event locations from the nodal array align well with the regional-array seismicity. Three main clusters are observed in the Peace River region from both the nodal and regional array data. The primary depth distribution of the nodal array events is between 4 and 6 km below the surface, suggesting the occurrence of events in the Precambrian basement. Additionally, a small cluster of events observed near (56.3°, -117°), located within 15 km of disposal wells, was not detected by the regional array (Figure 2a). This highlights the improved local resolution of seismic event locations achieved using the nodal array. Additional details regarding processing results, including event location uncertainties, are provided in Bui et al. (2025).

Figure 3 illustrates the relationship between event magnitudes and water injection volumes into the Leduc Formation. Injection activities began in the mid-1980s in two wells (102/14-25-085-19W5/00 and 102/16-23-085-19W5/00). The remaining wells commenced injection in the 2000s and early 2010s. Of these wells, four (102/14-25-085-19W5/00, 102/16-23-085-19W5/00, 100/06-29-084-18W5/02, and 100/02-20-085-19W5/00) continue to this day. Seismic data were obtained from the regional catalog through the earthquake dashboard (Alberta Earthquake Dashboard; Alberta Geological Survey, 2025); monitoring coverage was limited before 2014. A sharp increase in injection volumes after 2010 coincides with a rise in events exceeding magnitude 2, peaking between 2015 and 2017. This temporal alignment suggests a potential link between increased injection rates and increased seismicity.

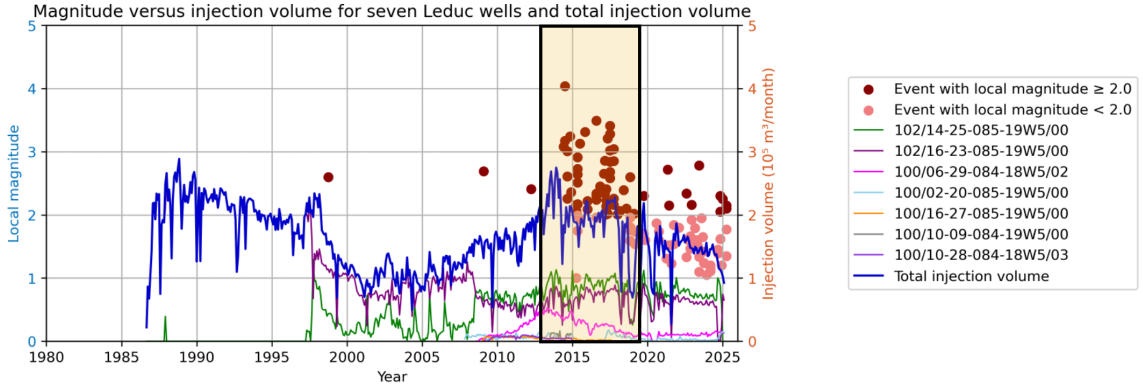



Figure 3. Event magnitude versus injection volume for Leduc wells near the North Peace River cluster.

Figure 4 shows the cross-correlation between seismic activity and injection volumes in the North Peace River cluster on annual scales. The results show a strong temporal association between seismic rates and injection volumes, persisting across multi-year lags and indicating slow stress transfer within the reservoir. Seismic data prior to 2014 were excluded due to limited monitoring coverage. Correlation at monthly resolution is less clear and probably not recommended because earthquake catalogs often miss smaller magnitude events that capture fine-scale variability, and disposal-induced seismicity typically shows significant time lags between operational changes and seismic response, reflecting gradual stress redistribution in the reservoir.

Figure 5a-c shows the results of applying the Foulger et al. (2023) questionnaire under three scenarios. This nine-question framework serves as a guide for assessing whether seismicity is natural or induced, with responses categorized as: (a) insufficient information, (b) evidence for natural origin, (c) inconclusive, and (d) evidence for induced origin. Although the questionnaire does not quantify contributions from specific operations (e.g., disposal wells into the Leduc Formation), it effectively identifies cases of induced seismicity. For the intermediate scenario,

61% of responses indicate an induced origin, 28% are equivocal, 11% reflect insufficient data, and none support a natural origin, strongly supporting an interpretation of induced seismicity.

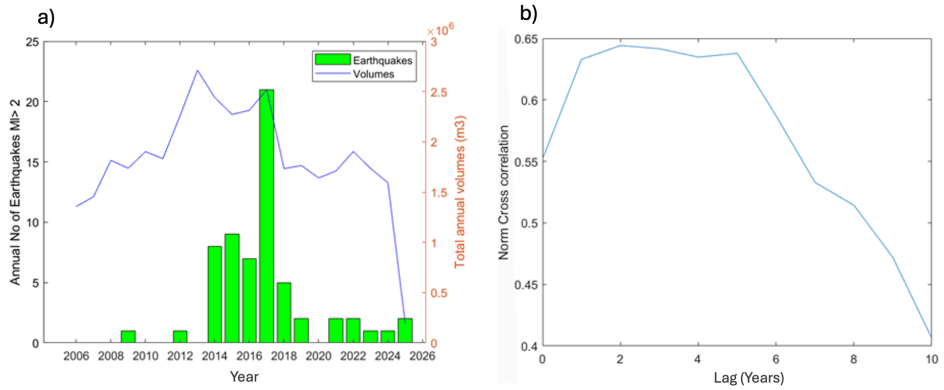



Figure 4. (a) Annual earthquake frequency and injection volumes for disposal operations in the Leduc Formation in the north Peace River region. (b) Normalized cross-correlation coefficient as a function of time lag (years), derived from cross-correlation between seismicity rates and injection rates.

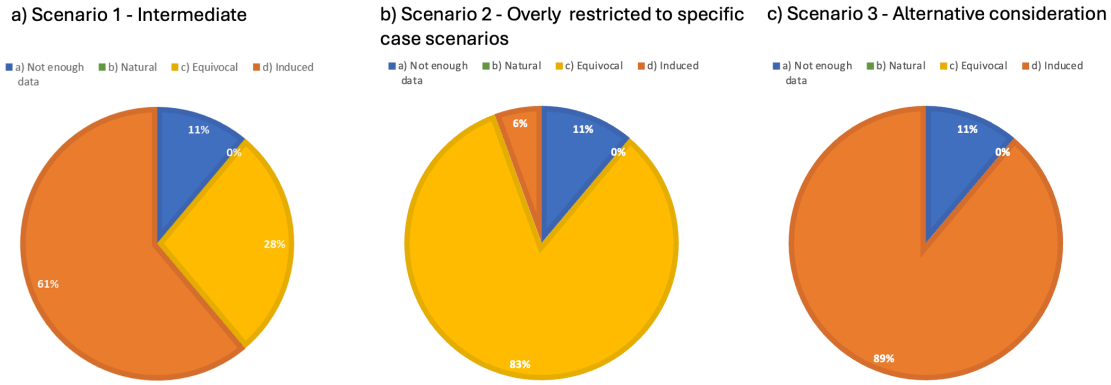



Figure 5. Questionnaire results: (a) Scenario 1 - Intermediate, (b) Scenario 2 - Overly restricted to specific cases, and (c) Scenario 3 - Alternative consideration.

## Conclusions

This study demonstrates the effectiveness of seismic nodal arrays in enhancing local-scale seismic monitoring. Applying a comprehensive processing workflow to three months of data from the north Peace River region yielded a catalog of 340 seismic events, with the largest having a magnitude of $M_L$ 2.83. Among these, 29 events had local magnitudes greater than or equal to 1, and 13 of these events were not previously identified by the regional seismic network. Despite the limited coverage of seven nodes, event locations aligned well with the regional catalog, with most occurring at depths between 4 and 6 km in the Precambrian basement. Notably, the nodal array identified a previously undetected cluster within 15 km of disposal wells, providing critical evidence for assessing sequence origin.

Correlation analysis indicates a strong temporal association between annual seismicity rates and injection volumes, suggesting a potential link between disposal activities and observed seismicity. Application of the Foulger et al. (2023) questionnaire further supports this interpretation, with 61%

of points favoring an induced origin, 28% being equivocal, and 11% reflecting insufficient data, while no points supported a natural origin scenario.

Future improvements should focus on enhancing workflow efficiency and accuracy by integrating advanced detection techniques, such as machine learning-based approaches, to reduce false alarms from STA/LTA and minimize the time required for manual event inspection and classification. Incorporating robust relocation methods could further improve location accuracy; however, careful validation is essential. These steps will optimize nodal array data processing and support a better understanding of seismic sequence evolution and origin assessment.

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