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Discerning Between Natural and Induced Seismicity by Using Evidence-Scoring Tools Designed to Evaluate Proposals of Induced Earthquakes: Application to the Reno and Kakwa Earthquake Sequences, Northwestern Alberta

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Abstract

The Alberta Geological Survey conducts comprehensive analyses of earthquake sequences to determine whether seismic clusters are of natural origin or induced by anthropogenic activities. These assessments are primarily guided by the criteria established by Davis and Frohlich (1993), which have been widely applied in identifying cases of induced seismicity in Alberta. However, recent evidence-scoring tools (questionnaires) were developed to better discern the nature of an earthquake sequence, addressing some of the limitations in the Davis and Frohlich (1993) criteria, including the issues posed by ambiguous and uncertain data. In this study, two questionnaires—Verdon et al. (2019) and Foulger et al. (2023)—were implemented to distinguish between natural and induced seismicity in two case studies: the Reno seismic cluster in the Peace River region and the Kakwa seismic cluster south of Grande Prairie. The feasibility of these questionnaires as effective tools to distinguish between industrially induced seismicity and natural earthquakes was evaluated by analyzing the available information for these two cases across two different time periods: using available information up to November 2022 and March 2023 for the Reno seismic cluster and using available information up to July 2022 and August 2023 for the Kakwa seismic cluster. This approach highlights the evolution in determining the origin of seismicity (whether natural or induced), driven by incorporating additional data and observations over time. For the seismic cluster near Reno, both questionnaires yielded ambiguous results using the information available up to November 2022. However, with acquisition of updated data up to March 2023, the results of both questionnaires became substantially inclined towards an induced seismicity origin. On the other hand, for the Kakwa seismic cluster, both questionnaire results consistently showed a strong inclination towards an induced seismicity origin, using available information up to July 2022 and August 2023.

These questionnaires are one of the multiple tools that a seismologist should use in the determination of natural and induced seismicity; a clear understanding of the regional geology and the physical processes that led to the earthquakes is critical. The relevance of such questionnaires depends on the reliability of the input parameters and the evaluation of the interpreter conducting the assessment; as such, they should be taken as an initial guide for evaluating induced seismicity while acknowledging their limitations and uncertainties.

1 Introduction

Alberta has a notable record of induced earthquakes dating back to the 1970s. Earthquakes from the 1970s to 2010 were predominantly associated with traditional oil and gas operations (e.g., Rocky Mountain House cluster; Wetmiller, 1986; Baranova et al., 1999). However, from 2011 onwards, earthquake frequency surged due to the rise of unconventional oil and gas activities, particularly hydraulic fracturing in the Duvernay Formation (Atkinson et al., 2016; Schultz et al., 2017; Wang et al., 2020). Since 2019, seismogenic disposal activities, such as those at Musreau Lake and Peace River, have become significant sources of seismic hazard in the province (Li et al., 2021; Reyes Canales et al., 2022; Schultz et al., 2023). Even though the seismic hazard from natural earthquakes is less significant than that posed by induced seismicity in recent years, natural earthquakes are present in Alberta, particularly in the Rocky Mountains and the Rocky Mountain Foothills regions. The proper identification of induced seismicity, distinguishing it from natural events, is critical since the seismic hazard from induced seismicity can be mitigated. To determine whether an earthquake sequence has an induced or natural origin, seismologists at the Alberta Geological Survey (AGS) analyze various aspects of an earthquake sequence. Multiple key questions guide this determination, following the seminal work from Davis and Frohlich (1993):

1) Are the events in an area where earthquakes are not typically frequent?
2) Has there been an increase in the frequency of earthquakes in this region?
3) Do the earthquakes coincide temporally with the suspected human activity?
4) Are the earthquakes within a reasonable distance from the suspected human activity?
5) Are the human-caused changes in stress on a fault large enough to explain the seismicity?

If the answer to most of these questions is yes, it suggests the earthquake was induced. Other aspects include the correlation between operational parameters and seismicity (e.g., rate of injection versus rate of earthquakes) and the swarm behaviour of the sequence (e.g., induced seismicity tends to show as earthquake swarms). The Davis and Frohlich (1993) criteria have been used to identify multiple induced seismicity cases in the province, including the earthquakes west of Fox Creek and near Red Deer, both related to hydraulic-fracturing activities in the Duvernay Formation. Also, induced seismicity cases related to disposal activities have been identified using these criteria, including the earthquakes east of Musreau Lake, related to injection disposal activities into the Winterburn Group, and the North Heart seismic cluster in the Peace River region, related to disposal into the Leduc Formation.

Differentiating between natural and induced seismicity can be challenging at times, particularly with new sequences or in areas with limited information. Since the initial work from Davis and Frohlich (1993), evidence-scoring tools (questionnaire-based format) have been developed to better discern the nature of earthquake sequences, addressing challenges posed by ambiguous and uncertain data. Such questionnaires, like Verdon et al. (2019) and Foulger et al. (2023), account for incomplete and ambiguous datasets, which are pertinent for emerging and evolving sequences. They also prioritize the spatiotemporal correlation between seismic sequences and operational activities over the specific source characteristics or regional seismicity features when weighing their responses. Considering the potential advantages of these questionnaires with respect to the original criteria from Davis and Frohlich (1993), they were implemented in two cases of seismicity: the Reno earthquake sequence in the Peace River region (southeast of Peace River) and the Kakwa earthquake sequence south of Grande Prairie, northwestern Alberta.

Prior to November 2022, seismicity near Reno, Peace River region, was sparse and isolated. However, seismic activity intensified before a local magnitude (M_L) 5.59 mainshock on November 29, 2022, with two M_L >4 events occurring just an hour prior. Furthermore, the sequence remained active, resulting in another mainshock on March 16, 2023, with a M_L = 5.09. In contrast, the seismicity related to the Kakwa cluster began in 2021 with small events and steadily intensified, reaching the first M_L >3 in August 2023, and then a M_L = 5.08 earthquake in February 2025.

In both examples, the suspected seismogenic activity corresponds to disposal activities into the Leduc Formation. One reason these areas with disposal activities were chosen as examples for implementing these questionnaires is that seismogenic disposal activities can be more challenging to identify, as they may require a long time frame to activate faults, sometimes years, in contrast to seismogenic hydraulic-fracturing activities that exhibit earthquakes during or within days after the activity. Also, earthquakes from seismogenic hydraulic-fracturing activities are usually constrained to areas close to the treatment wells (1–3 km), whereas disposal activities can activate faults at larger distances (more than 10 km in some cases). Thus, associating an earthquake sequence with hydraulic-fracturing activities is easier to constrain, and the use of questionnaires other than Davis and Frohlich's (1993) can better facilitate the determination of induced seismicity from disposal activities. The second reason for selecting these case studies was to contrast a scenario where sufficient information was available early in the assessment process with one requiring additional data collection and analysis to reduce uncertainty and reach a more definitive conclusion. Thus, cases like the Reno seismic cluster required additional information, including the deployment of a local array of seismic nodes and continued monitoring and observance of the sequence to help better constrain the origin of the earthquakes. This case contrasts with the Kakwa seismic cluster, where early analysis of the regional catalogue was sufficient for a strong indication of induced seismicity.

2 Evidence-Scoring Tools (Questionnaires) to Evaluate Proposals of Induced Seismicity

Induced seismicity questionnaires have been used to evaluate whether a sequence of earthquakes is induced or not. One of the earliest questionnaires was proposed by Davis and Frohlich (1993); see the questions in the "Introduction" (Section 1). These questions are focused on (1) the spatial relationship between earthquake epicentres and hypocentres and the proposed industrial activity, (2) the temporal correlation between seismic events and the timing of industrial operations, and (3) other questions involving whether the proposed activities could have caused sufficient stress changes at the earthquake locations. Even though the Davis and Frohlich (1993) criteria have been widely used to discern cases of induced seismicity in Alberta, they present some challenges, particularly when incorporating uncertainties, the lack of quantification in the outcome, and the uniformity in the relevance for each question. To address these issues, evidence-scoring tools, which follow a questionnaire-based approach, have been developed to better discern the nature of earthquake sequences, including those by Verdon et al. (2019) and Foulger et al. (2023). These recently developed approaches continue to prioritize the spatiotemporal correlation between seismic sequences and operational activities, while also considering weighting responses, given relevance, and uncertainty. These questionnaires refer to an expert-driven approach to evaluating earthquakes, not a survey of the general public.

2.1 Verdon et al. (2019) Questionnaire

The questionnaire suggested by Verdon et al. (2019) for distinguishing between natural and induced seismicity includes seven questions covering factors such as spatiotemporal correlations between seismicity and fluid injection activities, focal depths, regional seismicity, and possible activation mechanisms. Each question is given a score that indicates the level of support for either an induced origin (positive points) or a natural origin (negative points) based on the available evidence. The answers are weighted to express the level of confidence in the data available for each question. The Verdon et al. (2019) questionnaire generates two outputs: (1) the evidence strength ratio (ESR) and (2) the induced assessment ratio (IAR). The ESR describes the data quantity and quality, and is defined as

$$ESR = \frac{(|\text{Maximum negative points given available data}|+|\text{Maximum positive points given available data}|)}{\text{Total number of positive and negative points that can be scored in the framework}} \text{ x } 100 \quad (1)$$

A large ESR score indicates a significant amount of data, as well as a high level of confidence in it. On the other hand, the IAR expresses the likely origin of the earthquake sequence, and is defined as

$$IAR = \frac{\text{Summed score}}{|\text{Maximum points given available data}|} \text{ x } 100 \quad (2)$$

A positive IAR score indicates a tendency towards induced seismicity, whereas a negative IAR score indicates a tendency towards natural seismicity. The magnitude of the score reflects the strength of this tendency, with larger absolute values indicating greater support for one of the options. An IAR score close to zero suggests that the result is uncertain, with various pieces of evidence indicating different causes. Note that users must first assess the quality of the available evidence and determine whether there is enough evidence to answer the questions. If strong evidence is present, allowing the question to be fully answered, it is assigned an evidence weighting (EW) of 100%. If no evidence is available and the question cannot be answered, the question is not included.

2.2 Foulger et al. (2023) Questionnaire

The Foulger et al. (2023) questionnaire comprises nine questions, each with four possible responses: (a) insufficient information available, (b) evidence supporting a natural origin, (c) equivocal information, and (d) evidence supporting an induced origin. A single response is selected per question, and questions are assigned weights (either 10 points or 100 points) to yield a maximum score of 360 points. The term equivocal in this context does not imply partial support for either a natural or induced origin but rather indicates that the data is inconclusive. The questions are focused on (1) the relationship between earthquake locations and the proposed industrial activity, (2) the timing of the earthquakes in relation to the timing of the industrial activity, and (3) whether the proposed activities could have generated enough stress changes at the earthquake sites.

In contrast to the Verdon et al. (2019) scheme, the Foulger et al. (2023) scheme does not rely on numerical ratios. Instead, it presents the results as a coloured pie chart to prevent implying unrealistic precision in the findings. Notice that considerable weight is given to the questions focused on the spatiotemporal correlation between seismic sequences and operational activities; that is, 300 out of 360 points, or 83.3% of the points, directly depend on the spatiotemporal component.

3 Application of Questionnaires to the Reno and Kakwa Earthquake Sequences

3.1 Earthquake Sequence near Reno

A sequence of earthquake events occurred approximately 40 km southeast of the town of Peace River. Between November 2022 and March 2023, the AGS regional seismological network recorded over 245 events associated with this cluster. The most notable seismic event took place on November 29, 2022, registering a M_L = 5.59. The second largest event in this sequence occurred on March 16, 2023, with an estimated M_L = 5.09. Other seismic clusters have occurred in the Peace River region: one associated with disposal into the Leduc Formation (North Heart cluster) and another thought to be of natural origin (the North Peace River cluster).

There was isolated seismicity in the Reno area prior to the occurrence of the November 2022 events. Two events with M_L = 1.95 and M_L = 1.99 were identified in early 2017. After that, another isolated event occurred in October 2020, with a M_L = 1.61. There was a period of noteworthy activity in June 2021, with over 15 events, all with M_L <2.3. These events did not receive particular attention, considering their relatively low magnitudes and the assumption of a nearby natural seismic source. This situation rapidly changed with the seismicity detected in November 2022. Significant events preceded the November 29 mainshock event, including a M_L = 3.94 event on November 23, a M_L = 3.57 event on November 24, and two events with M_L >4 (M_L = 4.8 and M_L = 4.96) occurring an hour before the mainshock. The earthquake catalogue can be found at the AGS Earthquake Dashboard (Alberta Geological Survey, 2025).

With the occurrence of significant seismicity in the area, the AGS started a detailed evaluation of the well operations. The Peace River region hosts large-scale in situ oil sands extraction operations (de Klerk, 2020), with wells located relatively close to the Reno seismic cluster. However, the depths of the in situ oil sands operations are relatively shallow (<700 m from surface) compared to the Precambrian basement in the area (>2000 m from surface), thus making it challenging to identify a mechanism for induced seismicity. Importantly, the Precambrian basement typically hosts the roots of the faults that are activated during seismogenic industrial activity (Schultz et al., 2017). On the other hand, two active disposal wells close to the Reno seismic events were identified: one disposal well (WD-R1, 00/14-18-082-17W5/0; Figure 1a) injecting into the Leduc Formation (1920 m below surface, relatively close to the Precambrian basement), and a second disposal well (WD-R2, 00/06-14-082-18W5/0; Figure 1a) injecting into the Belloy Formation (790 m below surface). The well injecting into the Leduc Formation has been active since December 2012, whereas the Belloy Formation well has been active since September 2016. Figure 1a shows the location of the disposal activity, as well as the in situ oil sands extraction operations and earthquakes in the Reno seismic cluster up to March 2023. Figure 1b and c shows plots of the monthly injection volumes at both disposal wells.

The initial depth estimations set the mainshock, M_L = 5.59 event, depth at approximately 6 km and then 9 km below sea level (bsl) when more distant stations were included in the analysis. These depths would be considered too large to suggest any link with the disposal activity (0.79 and 1.92 km below surface). However, shortly after the November 2022 mainshock, the AGS deployed 10 seismic nodes in the area around the mainshock's epicentre. The purpose of using a local array of seismic nodes is to improve earthquake monitoring capacity and record subsequent aftershocks associated with the mainshock event with a higher location certainty than the regional seismic array. Using seismic nodal array data to associate a series of earthquakes with industrial activity has proven effective in previous cases. For instance, after the March 4, 2019, M_L = 4.24 mainshock event near Red Deer, the AGS deployed a seismic nodal array. The analysis of the seismic nodal array data from the aftershocks in Red Deer revealed a clear link with hydraulic-fracturing activities nearby, as well as an event location precise enough to interpret the activated fault structures (Wang et al., 2020).

The seismic nodes were deployed in the Reno area on December 6, 2022, and remained active until January 13, 2023. The first round of seismic nodes was collected by January 26, 2023, and sent a few days later to a third party, Nanometrics Inc. (Nanometrics), to be processed at the earliest opportunity. Together with the raw waveform data and the sensor information, the AGS provided a velocity model designed for the Reno area. Before the November 2022 mainshock event, the AGS was employing a one-dimensional (1D) velocity model calibrated for the Fox Creek region to analyze seismicity in the Reno area, which may have introduced inaccuracies in earthquake location estimates. After the mainshock, the AGS used sonic logs (compressional-wave velocity [Vp]) from wells in the Reno area to build a new 1D velocity model of the sedimentary strata over which the logs were run. This local velocity model for the Reno area was developed to improve the accuracy of the earthquake location. Two other rounds of seismic nodes were deployed and collected between January and April 2023. The results and interpretation of the latter two rounds of seismic nodal array data are to be described in a later study.

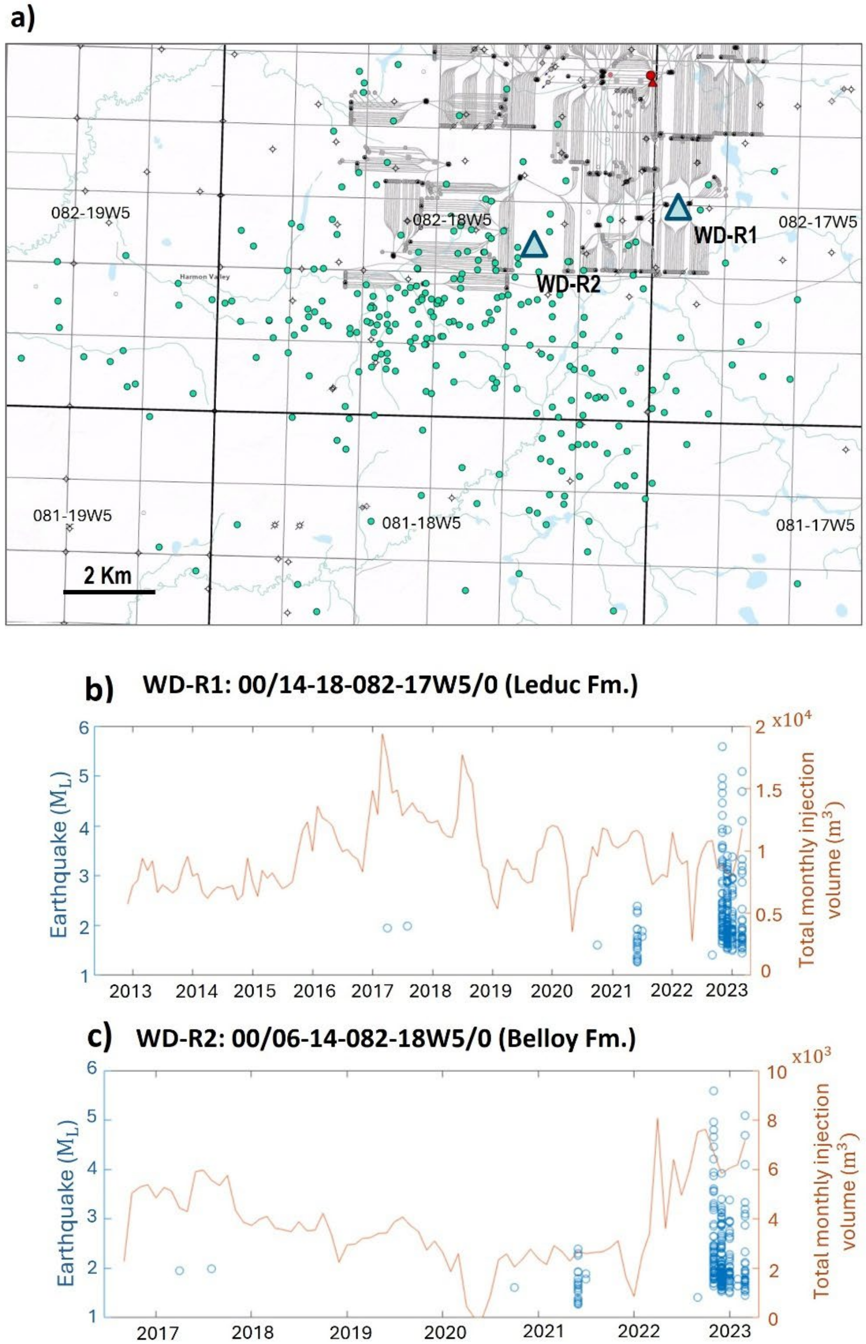


Figure 1. (a) Seismicity in the Reno area (green dots), northwestern Alberta, up to March 2023 (Alberta Geological Survey, 2025). The disposal wells WD-R1 (00/14-18-082-17W5/0), injecting into the Leduc Formation, and WD-R2 (00/06-14-082-18W5/0), injecting into the Belloy Formation, are shown as blue triangles. Operational sites in the area, including other disposal wells (red dots/triangle), multilateral wells for in situ oil sands production in shallow Cretaceous formations (black dots with thin grey lines, which represent traces of deviated and horizontal well paths), and other oil and gas well operations (grey symbols) are also shown (Alberta Energy Regulator, 2025). The monthly injection volumes (orange line; Alberta Energy Regulator, 2025) into the (b) Leduc Formation disposal well up to March 2023 and (c) Belloy Formation disposal well up to March 2023, are plotted along with the local magnitudes (M_L) of earthquakes in the area (blue circles; Alberta Geological Survey, 2025).

The processing results of round 1 of data from Nanometrics were delivered to the AGS on March 17, 2023. Nanometrics provided four earthquake catalogues that corresponded to the use of two different 1D velocity models (Fox Creek and Reno velocity models) and two different location algorithms (inversion and grid search methods). From those four earthquake catalogues, the catalogue resulting from the Reno velocity model and the grid search location method was prioritized. The Reno velocity model better captures the specific geological conditions of the Reno area; the Fox Creek velocity model was provided as an additional model to verify the previous event location inaccuracies. Also, the results from the grid search method were prioritized over those from the inversion method since the inversion method required a modification of the Reno velocity model to enable the processing of the earthquake data and execution of the algorithm.

Figure 2a and b shows a comparison between the earthquake locations from the regional AGS catalogue (Alberta Geological Survey, 2025) and the earthquake locations from the local nodal array data. Despite the differences in the time periods covered by each catalogue, a substantial improvement in the resolution can be inferred by the nodal array data, enabling a clear interpretation of two subclusters. Figure 3a and b shows two depth profiles from the nodal array data (results using the Reno velocity model and the grid search method). The two disposal wells in the area (WD-R1 injecting into the Leduc Formation, and WD-R2 injecting into the Belloy Formation) and the estimated depths of key formations (Belloy and Leduc formations, as well as the top of the basement) are included in the figure as reference. Notice the presence of two rough lineaments outlined by the earthquakes, which can be interpreted as two activated faults, with depths ranging between 1.5 and 6 km bsl. Notice in particular that the earthquakes reach depths as shallow as 1.9 km below the surface. In other words, the initial processed results from the seismic nodal array data point out that the earthquakes are shallower than previously expected (first estimated at 6 km bsl, then at 9 km bsl when regional stations were included in the analysis), reaching depths comparable to one of the disposal targets (WD-R1 at 1.92 km below surface). This pattern of relatively shallow activities activating basement-rooted faults, resulting in deeper earthquakes than the target injection, is typical in cases of disposal induced seismicity (e.g., the disposal activities causing induced events in Oklahoma [Keranen et al., 2013]). On the other hand, the interpreted activated faults do not appear to reach the levels of the Belloy Formation, making the association between the earthquakes and the disposal injection into the Belloy Formation unclear. Finally, two unusual horizontal lineaments are observed at approximately 1.2 and 1.6 km bsl, which are likely artifacts resulting from the location process (e.g., the low-velocity zone in the input velocity model).

Another critical piece of evidence is that after the November 2022 events, the seismicity remained active, with clear ruptures in the expected seismicity rate of decay (Omori's law; Omori, 1894), particularly in March 2023. A sizeable earthquake occurred on March 16, 2023, with an estimated $M_L = 5.09$, while disposal activities remained active. This event confirmed that the sequence has an anomalous frequency of earthquakes for the area, resembling a nonstationary seismic behaviour typical of induced seismicity. Figure 4a shows a three-dimensional (3D) view of the nodal array data (round 1) with respect to the disposal activity, as well as a plot of injection rates from both disposal activities and the magnitude of seismic events over time (Figure 4b and c). As described before, the two interpreted structures (west and east subclusters) reach the levels of the Leduc Formation. There is no evidence that these structures reach the shallower depths of the Belloy Formation. In fact, more than 1100 m of strata separate the Leduc and Belloy formations, without any clear evidence of faulting extending beyond the Leduc Formation (see Figure 5 for a schematic geological cross-section of the Reno area). This is part of the reason why the large-scale in situ oil sands extraction was dismissed as a causal activity of seismicity. The other reason is that the primary mechanism behind fault activation is the increase of pore pressure (Ellsworth, 2013), and bitumen extraction would decrease pore pressure (in contrast to the expected pore pressure increase from disposal activities). Furthermore, given the lack of connection between the seismicity and the shallower depths of the Belloy Formation, it was decided to focus the questionnaire application on WD-R1, which injects into the Leduc Formation.

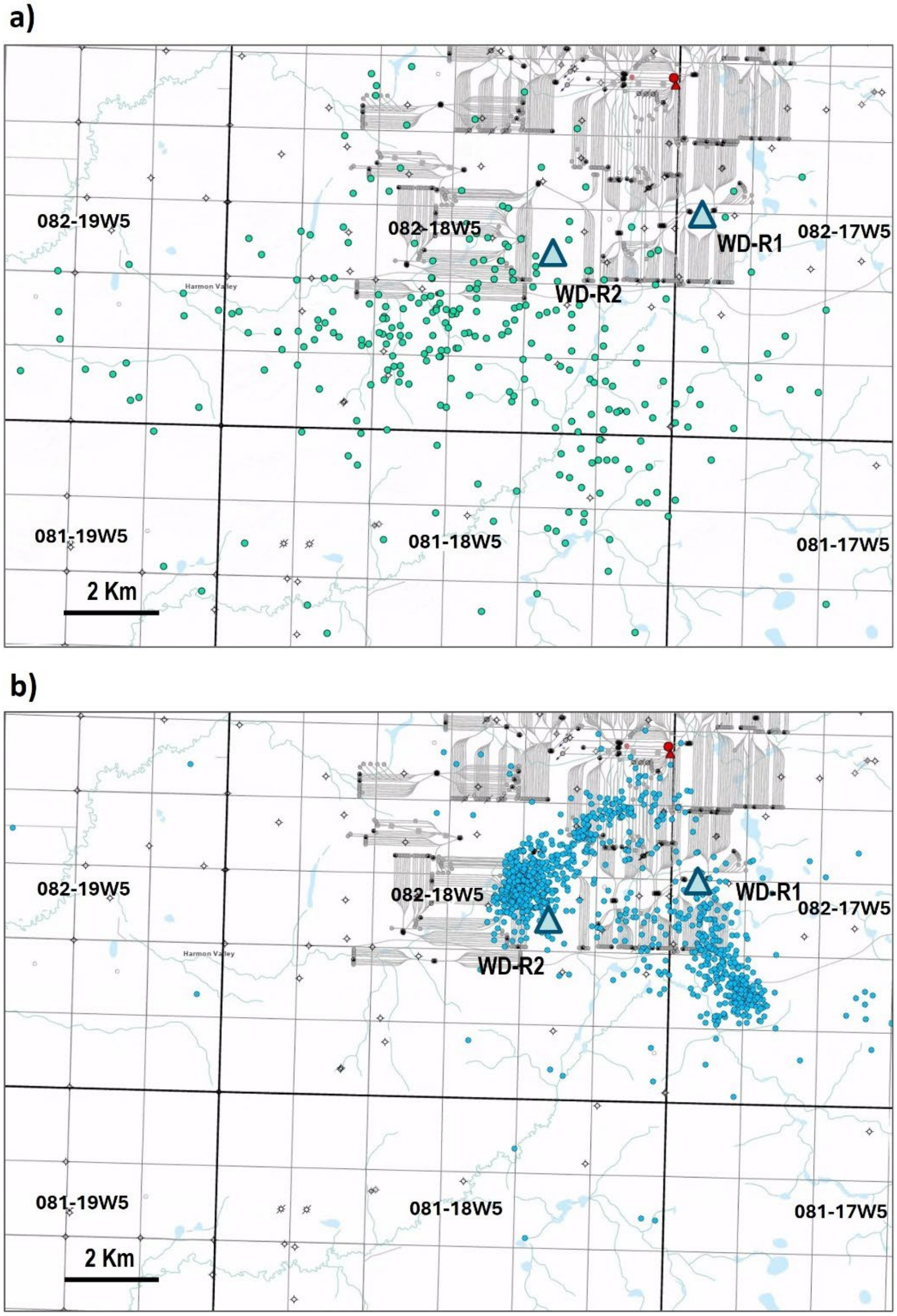


Figure 2. Seismic events in the Reno cluster, northwestern Alberta, recorded by the (a) Alberta Geological Survey (AGS) regional array (green dots), data up to March 2023 (Alberta Geological Survey, 2025) and (b) local array of seismic nodes deployed by the AGS (blue dots), data from December 6, 2022 to January 13, 2023. The nodal array data provided a high-resolution catalogue of the events resulting after the local magnitude 5.59 event on November 29, 2022. Disposal wells WD-R1 (00/14-18-082-17W5/0) and WD-R2 (00/06-14-082-18W5/0) are shown as blue triangles. Operational sites in the area, including other disposal wells (red dots/triangle), multilateral wells for in situ oil sands production in shallow Cretaceous formations (black dots with thin grey lines, which represent traces of deviated and horizontal well paths), and other oil and gas well operations (grey symbols), are also shown (Alberta Energy Regulator, 2025).

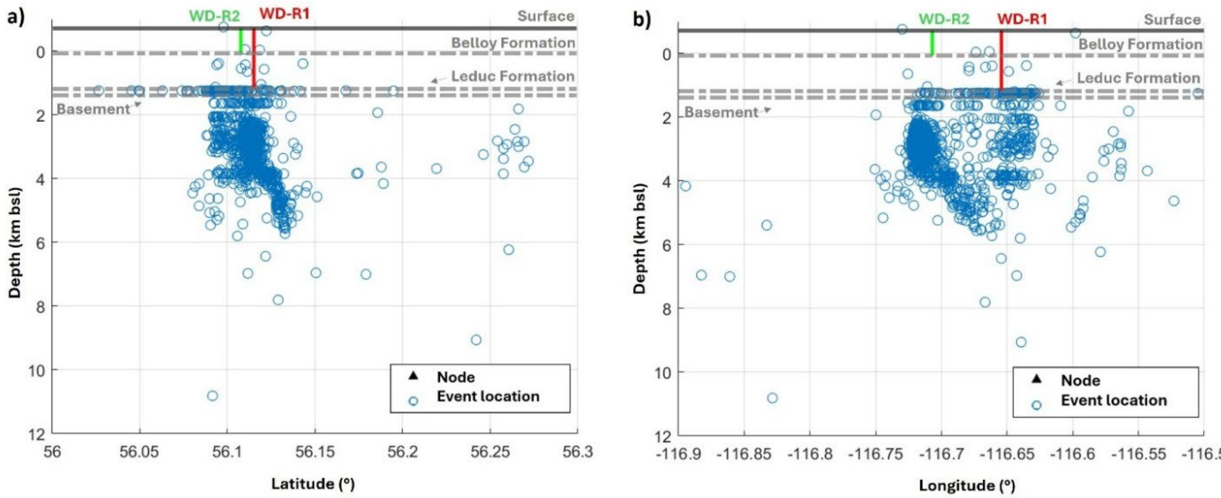


Figure 3. Depth profiles of seismic events (blue circles) in the Reno cluster, northwestern Alberta: (a) south-north cross-section; (b) west-east cross-section. Data recorded by the local seismic nodal array between December 6, 2022 and January 13, 2023. Two disposal wells are in the immediate location of the cluster: WD-R1 (00/14-18-082-17W5/0) injecting into the Leduc Formation (1.92 km below surface) and WD-R2 (00/06-14-082-18W5/0) injecting into the Belloy Formation (0.79 km below surface). Abbreviation: bsl, below sea level.

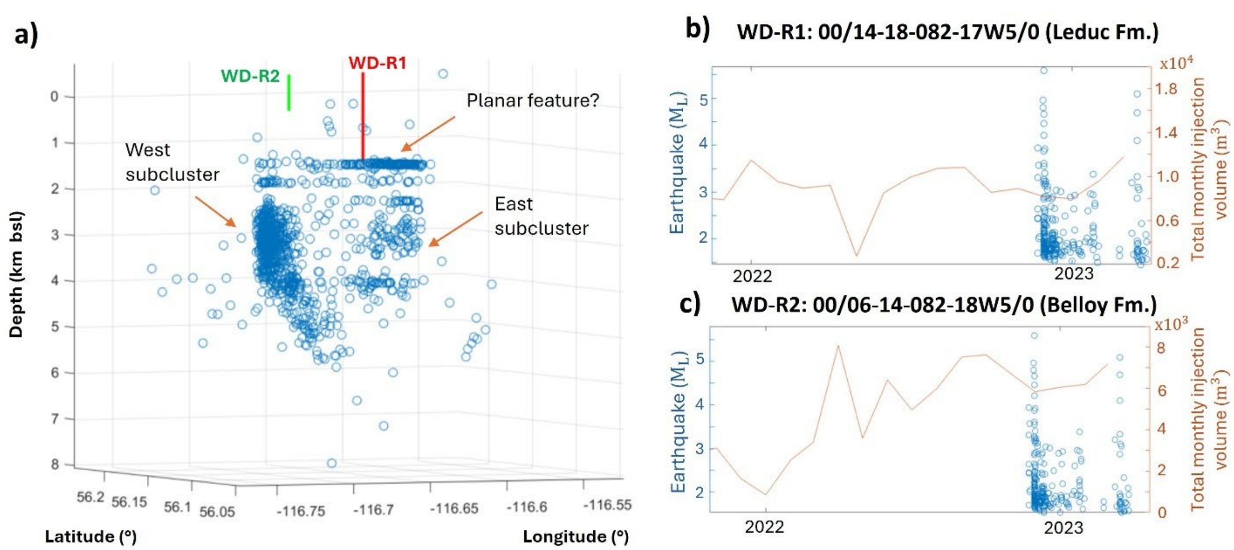


Figure 4. (a) A three-dimensional view of the seismic nodal array data (blue circles) from the Reno area, northwestern Alberta, December 6, 2022 to January 13, 2023. Two disposal wells (WD-R1 [00/14-18-082-17W5/0] and WD-R2 [00/06-14-082-18W5/0]) in the immediate vicinity of the seismic cluster are also plotted for reference. The monthly injection volumes into the (b) Leduc Formation (WD-R1) and (c) Belloy Formation (WD-R2) disposal wells (Alberta Energy Regulator, 2025), are plotted along with the local magnitudes (M_L) of earthquakes (blue circles) in the area, from one year prior to the M_L = 5.59 mainshock event (November 29, 2022) to March 2023 (Alberta Geological Survey, 2025). Abbreviation: bsl, below sea level.

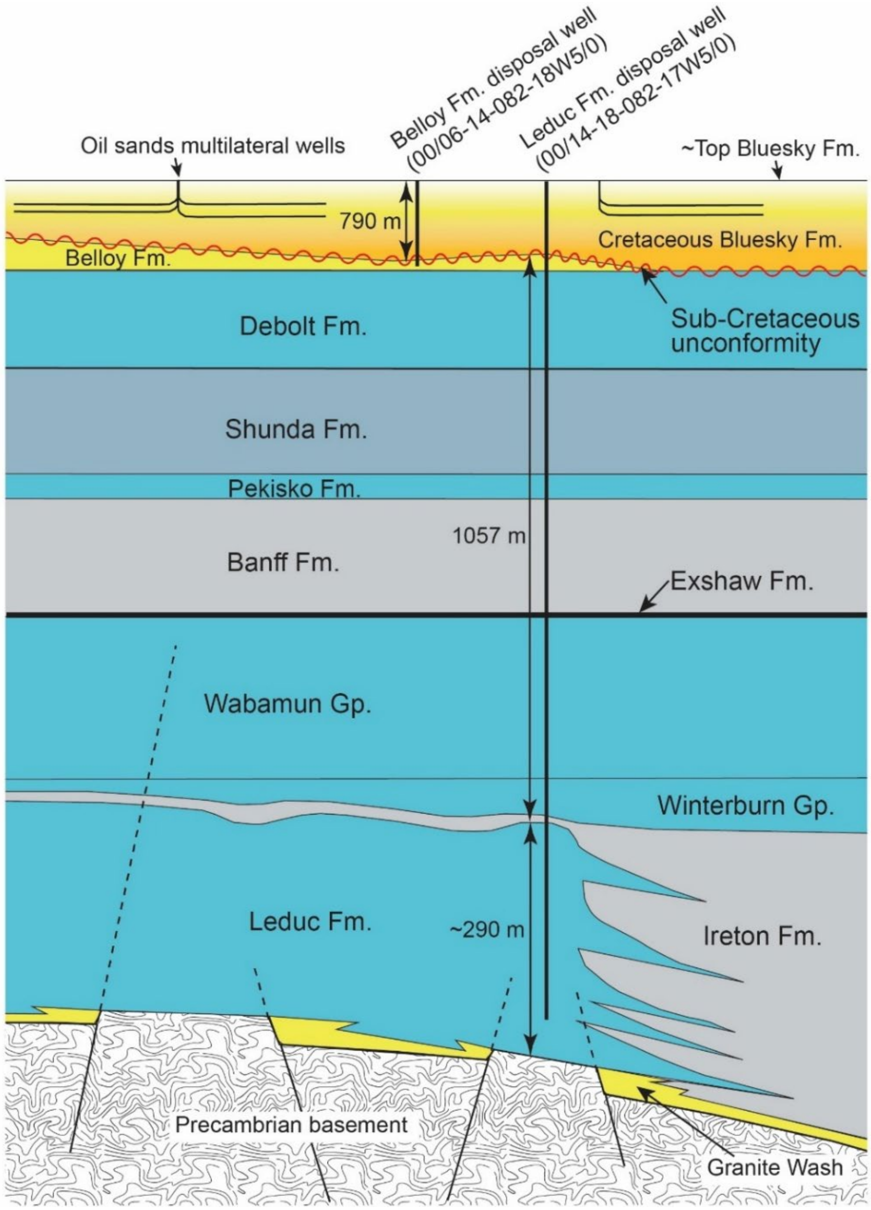


Figure 5. Schematic geological cross-section of the Reno area, northwestern Alberta, showing disposal wells WD-R1 (00/14-18-082-17W5/0) and WD-R2 (00/06-14-082-18W5/0), which are injecting into the Leduc Formation and Belloy Formation, respectively. Notice that the Leduc Formation either directly overlies the Precambrian basement or is separated by a thin interval of Granite Wash sandstone; thus, postulating connections with the basement-rooted faults (thin solid and dashed lines) is justifiable.

In Figures 3 and 4, some observed horizontal lineaments (planar features) can be considered artifacts produced by rapid changes in the velocity model. These artifacts are corrected in subsequent reprocessing of the nodal array data and do not change the overall previous location of the seismicity and interpreted structures (west and east subclusters).

3.1.1 Application of the Verdon et al. (2019) Questionnaire

The Verdon et al. (2019) questionnaire was applied to the Reno earthquake sequence using the information available (1) up to November 2022 and (2) up to March 2023. Table 1 shows a summary of the chosen answers. The first question refers to the regional seismicity in the area. In November 2022, there was an apparent change in the seismicity around Reno. Some sporadic events with magnitudes of M_L >2 had been detected in the past, but they could have been attributed to natural seismicity. One important point is that, from a regional perspective, the AGS assumed other seismic clusters in the Peace River region were natural in origin, largely because the area contains the Peace River Arch—a cratonic antiform comprising Precambrian basement rocks that has a protracted and complicated tectonic history (e.g., Cant and O'Connell, 1988). Thus, given the information available in November 2022, option 'b' was chosen (Table 1). However, by March 2023, particularly after the M_L = 5.09 on March 16, it was clear that the sequence marked a distinctive departure from the previously observed rates, thus, option 'c' was chosen (Table 1). With respect to the depth, nothing indicated that the Reno seismic events were significantly shallower than the previously classified natural events in the area, thus, option 'd' was chosen (Table 1). Given the limitations of the regional seismological network (sparse station coverage) and the initially suspected mix of causes between natural and induced seismicity, this question was given a weight of 0.5 out of 1.

The second question refers to the temporal coincidence between the onset of events and industrial activities. Option 'c' was chosen for both time periods since the events were occurring at the same time as the suspected activity (Table 1). The third question refers to the correlation between injection volumes and seismicity. A strong correlation was not identified between seismicity and activities at WD-R1, using the data available in November 2022, thus, option 'a' was chosen (Table 1). However, the injection rates continued after the November 2022 mainshock matching the equally persistent seismicity since then. By using cross-correlation analysis (see Appendix 1, Figure 13), an increase in the correlation was identified between injection rates and seismicity from November 2022 to March 2023 (from 0.12 to 0.16 at a three-month lag for WD-R1). Furthermore, the occurrence of seismic events during periods of high injection volumes in 2017 can be identified (Figure 1b). Thus, the events from 2021 could be matched with a rise in injection rates that started in mid-2020. With these observations, option 'b' was chosen for up to March 2023, as some temporal correlation between the seismicity and industrial activity is suggested (Table 1). Both questions 2 and 3 were given a weight of 1.

For the fourth question, the initial data in November 2022 indicated that the mainshock was at a relatively large depth versus the disposal activities (6 to 9 km bsl versus 0.79 and 1.92 km below surface). Therefore, option 'a' was chosen, but with a high level of uncertainty given the limited coverage of the regional array (a weight of 0.3 was given to the question; Table 1). Due to the high resolution of event locations from the nodal array data, option 'c' was chosen for up to March 2023 (Table 1). The seismic nodal array data played a crucial role in constraining the depth of the sequence, as third-party processed results represented the highest-quality data available at the time. These results indicated that the earthquakes occurred at depths comparable to those of the suspected industrial activity, specifically, disposal operations within the Leduc Formation. Furthermore, a weight of 1 was given since the high-resolution data recorded at separate times showed relatively similar depths for the events. For the fifth question, both regional and nodal array data indicated that the earthquakes were sufficiently close to the activities, given the putative causative mechanism; thus, option b was chosen for both time periods, with a weight of 1 given to this question (Table 1). The sixth question was not included for up to November 2022 information given the available data, as it is challenging to provide evidence for a clear mechanism based on the relatively large distance between the mainshock and disposal activities. However, based on the information available as of March 2023, it is reasonable to infer that the disposal activity can lead to enough pore-pressure and poroelastic stress changes to activate basement-rooted faults. Therefore, for question six, option 'b' was chosen, with a weight of 1 (Table 1). Finally, question seven was not included due to a lack of available information regarding the source mechanism of the earthquakes.

Table 1. Answers to the Verdon et al. (2019) questionnaire for the Reno earthquake sequence, northwestern Alberta, with the information available up to November 2022 and March 2023. Modified from Verdon et al. (2019) © Seismological Society of America. Abbreviations: N/A, not included; Q, question.

Question and Possible Answers	Answer Score	Answer for up to November 2022	Answer for up to March 2023
Q1. Has there been previous (either historical or instrumental) seismicity at the same site, or within the same regional setting?	**Score**	**Evidence weight: 50%**	**Evidence weight: 50%**
a) Earthquakes have previously occurred in the vicinity of the site, with similar rates and magnitudes	-5	No (0 resulting points)	No (0 resulting points)
b) Earthquakes have previously occurred within the same regional setting, with similar rates and magnitudes	-2	Yes (-1 resulting points)	No (0 resulting points)
c) Earthquakes have not occurred at similar rates or magnitudes within the regional setting	5	No (0 resulting points)	Yes (2.5 resulting points)
d) Past earthquakes occurred at similar depths within the regional setting	-3	Yes (-1.5 resulting points)	Yes (-1.5 resulting points)
e) Earthquakes are significantly shallower than any past events that have been observed within the regional setting	3	No (0 resulting points)	No (0 resulting points)
Q2. Is there a temporal coincidence between the onset of events and the industrial activities?	**Score**	**Evidence weight: 100%**	**Evidence weight: 100%**
a) The earthquake sequence began prior to the commencement of industrial activity	-15	No (0 resulting points)	No (0 resulting points)
b) The earthquake sequence did not begin until a significant period of time after the cessation of industrial activity	-5	No (0 resulting points)	No (0 resulting points)
c) The earthquake sequence began while the industrial activity was ongoing	5	Yes (5 resulting points)	Yes (5 resulting points)
Q3. Are the observed seismic events temporally correlated with the injection or extraction activities?	**Score**	**Evidence weight: 100%**	**Evidence weight: 100%**
a) The earthquakes are coincident with the industrial activity, but there is minimal correlation	-4	Yes (-4 resulting points)	No (0 resulting points)
b) There is some temporal correlation between the seismicity and the industrial activity	4	No (0 resulting points)	Yes (4 resulting points)
c) There is a strong temporal correlation between the seismicity and the industrial activity (e.g., between rates of injection and rates of seismicity)	15	No (0 resulting points)	No (0 resulting points)
Q4. Do the events occur at similar depths to the activities?	**Score**	**Evidence weight: 30%**	**Evidence weight: 100%**
a) Earthquakes do not occur at the same depth, and there is no plausible mechanism by which stress or pressure changes could be transferred to these depths	-4	Yes (-1.2 resulting points)	No (0 resulting points)
b) Earthquakes do not occur at the same depth, but plausible mechanisms exist by which stress, or pressure changes could be transferred to these depths	2	No (0 resulting points)	No (0 resulting points)
c) Earthquakes occur at similar depths to the industrial activity	3	No (0 resulting points)	Yes (3 resulting points)
Q5. Is there spatial collocation between events and the activities?	**Score**	**Evidence weight: 100%**	**Evidence weight: 100%**
a) Earthquakes are distant from the activities, given the putative causative mechanism	-10	No (0 resulting points)	No (0 resulting points)
b) Earthquakes are sufficiently close to the activities, given the putative causative mechanism	5	Yes (5 resulting points)	Yes (5 resulting points)
c) If earthquake loci change with time, this change is consistent with the industrial activity, for example, growing radially from a well or shifting in response to the start of a new well	10	N/A	N/A
Q6. Is there a plausible mechanism to have caused the events?	**Score**	**Evidence weight: N/A**	**Evidence weight: 100%**
a) No significant pore-pressure increase or decrease occurred that can be linked in a plausible manner to the event hypocentral position	-5	N/A	No (0 resulting points)
b) Some pore-pressure or poroelastic stress change occurred that can be linked in a plausible manner to the event hypocentral position	2	N/A	Yes (2 resulting points)
c) A large pore-pressure or poroelastic stress change occurred that can be linked in a plausible manner to the event hypocentral position	5	N/A	No (0 resulting points)
Q7. Does the source mechanism indicate an induced event mechanism?	**Score**	**Evidence weight: N/A**	**Evidence weight: N/A**
a) The source mechanisms are consistent with the regional stress conditions	0	N/A	N/A
b) Source mechanisms are not consistent with the regional stress conditions, but are consistent with a putative causative mechanism (e.g., thrust faults above a subsiding reservoir)	4	N/A	N/A

Figure 6a and b shows a summary of the ESRs and IARs for the Reno earthquake sequence for two different time periods. The green and orange bars refer to the total amount of points per question that can be achieved, considering the certainty factor. The blue bars refer to the number of points obtained per question in this case study. Using the information available up to November 2022, an ESR = 66% and an IAR = 7% were obtained, suggesting a good amount of evidence and an ambiguous inclination towards induced seismicity. However, once the seismic nodal array data was included in the analysis, as well as observations of persistent seismicity in the following months, an ESR = 82% and an IAR = 54% were obtained. The values from March 2023 show more substantial available evidence and a clear inclination towards induced seismicity.

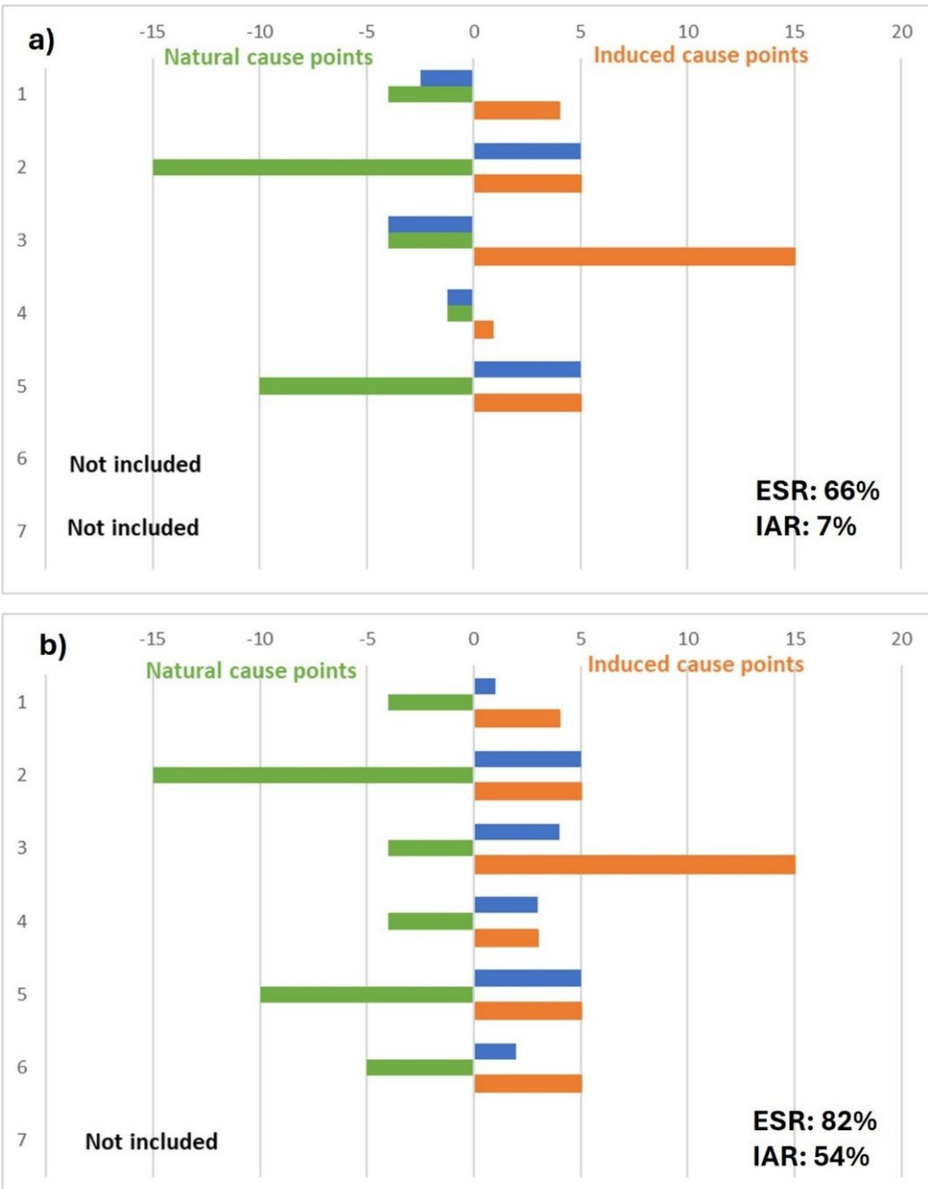


Figure 6. Summary (blue bars) of the evidence strength ratio (ESR) and induced assessment ratio (IAR) for the Reno earthquake sequence, northwestern Alberta, using the available information up to (a) November 2022 and (b) March 2023, based on the Verdon et al. (2019) questionnaire. The points are adjusted based on the certainty of data available. The green and orange bars refer to the total amount of points per question that can be achieved, considering the certainty factor.

3.1.2 *Application of the Foulger et al. (2023) Questionnaire*

Similar to the previous questionnaire, the Foulger et al. (2023) questionnaire was applied to the Reno earthquake sequence using the information available up to November 2022 and up to March 2023. Table 2 shows a summary of the chosen answers. The first question refers to the temporal occurrence of the sequence. Option 'd' was chosen for both time periods since the potential induced earthquakes (PIE) began while industrial activity was substantial (Table 2). Earthquakes in the Reno area were recorded as early as 2017, but the injection into the Leduc Formation started four years prior in December 2012. The second and third questions refer to epicentral and hypocentral locations, respectively. For the second question, option 'd' was chosen for both time periods since it is unequivocal that the earthquakes are within the likely area of environmental modulation by industrial activity in map view (around the epicentre; Table 2). For the third question, option 'c' was chosen given the available information up to November 2022 and option 'd' was chosen given the available information up to March 2023 (Table 2). The initial information up to November 2022 showed earthquake depths that would be considered too large for any link with the disposal activity. When the high-resolution nodal array data were analyzed, the revised depths showed a clear link between seismicity and the suspected injection activity.

The fourth question refers to the correlation between injection volumes and seismicity. As explained earlier, a clear correlation between seismicity and WD-R1 activity is not obvious using the information available up to November 2022, thus, option 'b' was chosen (Table 2). However, some temporal correlation between the earthquakes and specific industrial events can be inferred from the up to March 2023 data, particularly by the persistent seismicity after November 2022, while injection rates continued relatively unaltered. Option 'c' was chosen for this time period (Table 2). The fifth and sixth questions refer to the epicentral and hypocentral locations of the pre-industrial earthquakes. Option 'c' was chosen for both questions and both time periods since natural earthquakes with a relatively similar depth have been assumed to have occurred in the broader region around the site (Table 2). The seventh question refers to the information on the focal mechanism, this information was not available for either time period so option 'a' was chosen (Table 2). The eighth and ninth questions refer to any additional seismic or nonseismic data, respectively, available to determine the origin of the sequence. By November 2022, this information was not available so option 'a' was chosen for both questions (Table 2). Other seismic evidence, like the persistent seismicity, the departure of the aftershock sequence after November 2022, and the radical change in the style of seismicity, correspond to an induced seismicity case so option 'd' was chosen for question eight for the up to March 2023 period (Table 2). By March 2023, nonseismic information was not at the disposal of the AGS so option 'a' was chosen for question nine (Table 2).

Figure 7a and b shows pie charts summarizing the results of the Foulger et al. (2023) questionnaire for the Reno earthquake sequence for the two different time periods. Using the information available up to November 2022, 33% of the points are inclined towards equivocal data, 31% of the points towards induced seismicity origin, 28% of the points towards natural seismicity, and 8% of the points towards insufficient or unavailable data. The results from up to November 2022 suggest an unclear origin for the sequence. However, using the information available up to March 2023, 61% of the points are inclined towards induced seismicity origin, 33% of the points towards equivocal data, 6% of the points towards insufficient or not available data, and no points towards natural seismicity. As mentioned before, the rapid and necessary deployment of the nodal array and further observation in the evolution of the sequence up to March 2023 helped to constrain the origin of the sequence better.

Table 2. Answers to the Foulger et al. (2023) questionnaire for the Reno earthquake sequence, northwestern Alberta, with the information available up to November 2022 and March 2023. Modified from Foulger et al. (2023). Abbreviation: PIE, potential induced earthquake.

Question	Possible Answers	Points for up to November 2022	Points for up to March 2023
Question 1 PIE-temporal	**Did the PIE sequence onset before, during, or after the industrial activity?**		
	a) Insufficient information available	0	0
	b) The PIE sequence began before the onset of the industrial activity	0	0
Weight of question	c) The PIE sequence began while the industrial activity was minimal or after cessation	0	0
10 points	d) The PIE sequence began while the industrial activity was substantial	10	10
Question 2 PIE-epicentres	**Is there spatial collocation between the PIEs and the likely area of environmental modulation by the industrial activity?**		
	a) Insufficient information available	0	0
	b) The PIEs are outside the likely area of environmental modulation by the industrial activity	0	0
Weight of question	c) The PIEs are peripheral to the likely area of environmental modulation by the industrial activity	0	0
100 points	d) The PIEs are within the likely area of environmental modulation by the industrial activity	100	100
Question 3 PIE-hypocentres	**Is there spatial collocation between the PIEs and the likely area of environmental modulation by the industrial activity?**		
	a) Insufficient information available	0	0
	b) The PIEs are beneath the likely volume of environmental modulation by the industrial activity	0	0
Weight of question	c) The PIEs are peripheral to the base of the likely volume of environmental modulation by the industrial activity	100	0
100 points	d) The PIEs are within the likely volume of environmental modulation by the industrial activity	0	100
Question 4 PIE-temporal	**Is there a temporal correlation between PIEs and specific industrial events?**		
	a) Insufficient information available	0	0
	b) There is little or no temporal correlation between the PIEs and specific industrial events	100	0
Weight of question	c) There is a weak temporal correlation between the PIEs and specific industrial events	0	100
100 points	d) There is a strong temporal correlation between the PIEs and specific industrial events	0	0
Question 5 Pre-industrial earthquake epicentres	**Is there evidence for pre-industrial earthquakes at or near the site of the PIEs?**		
	a) Insufficient information available	0	0
	b) Pre-industrial earthquakes occurred at or near the site of the PIEs	0	0
Weight of question	c) Pre-industrial earthquakes occurred only in the wider region around the site of the PIEs	10	10
10 points	d) Pre-industrial earthquakes did not occur at or near the site of the PIEs or in the wider region around it	0	0
Question 6 Pre-industrial earthquake hypocentres	**Is there evidence for pre-industrial earthquakes in the same volumes as the PIEs?**		
	a) Insufficient information available	0	0
	b) Pre-industrial earthquakes occurred at or near the site of the PIEs at similar or shallower depths	0	0
Weight of question	c) Pre-industrial earthquakes occurred only in the wider region around the site of the PIEs at similar or shallower depths	10	10
10 points	d) Pre-industrial earthquakes did not occur at or near the site of the PIEs or in the wider region around it at similar or shallower depths	0	0
Question 7 Focal mechanism	**Are there focal mechanisms consistent with a natural and/or induced earthquake cause?**		
	a) Insufficient information available	10	10
	b) The focal mechanisms are consistent with the regional stress and not consistent with the proposed induction mechanism	0	0
Weight of question 10 points	c) The focal mechanisms are consistent with the regional stress and are consistent with the proposed induction mechanism OR the focal mechanisms are not consistent with the regional stress and are consistent with the proposed induction mechanism	0	0
	d) The focal mechanisms are not consistent with the regional stress and are consistent with the proposed induction mechanism	0	0
Question 8 Other seismic data	**Are there other seismic data to support a natural or induced cause (e.g., swarm, foreshock-aftershock pattern, b-value, total number of earthquakes, radical change in style of seismicity, stress release corresponding to the earthquake magnitude of seismicity)?**		
	a) Insufficient information available	10	0
Weight of question	b) Other seismic data support a natural origin	0	0
10 points	c) Other seismic data are equivocal	0	0
	d) Other seismic data support an induced origin	0	10
Question 9 Other nonseismic data	**Are there nonseismic data that support a natural or induced cause (e.g., direct nucleation effects, precursory surface deformation)?**		
	a) Insufficient information available	10	10
Weight of question	b) Other nonseismic data support a natural origin	0	0
10 points	c) Other nonseismic data are equivocal	0	0
	d) Other nonseismic data support an induced origin	0	0

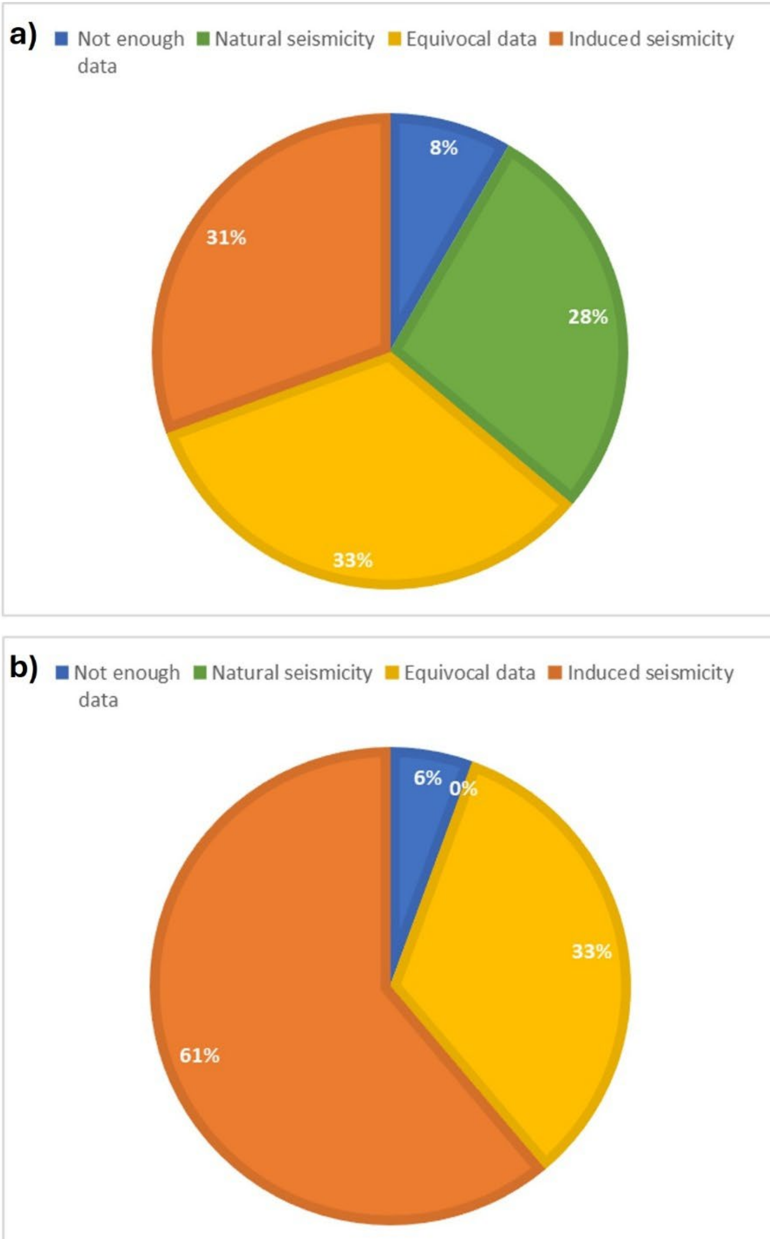


Figure 7. Pie chart generated from all of the responses to the questionnaire from Foulger et al. (2023) using the available data for the Reno earthquake sequence, northwestern Alberta, up to (a) November 2022 and (b) March 2023.

3.2 Earthquake Sequence in the Kakwa Area

Seismic events in the Kakwa area were first detected in March 2021, with an event magnitude of M_L = 1.5. Other clusters had been previously identified in a regional context, including the seismic clusters near Musreau Lake (Li et al., 2021), which are related to disposal activities in the Winterburn Group, and the Gold Creek cluster, related to disposal activities in the Leduc Formation. Furthermore, over 40 km away to the east, widespread seismicity related to hydraulic-fracturing activities near Fox Creek had been studied since 2013. The Kakwa seismic cluster has remained active since its first detection, with increasing frequency of events over time, reaching its first event with a M_L >3 in July 2022. Three disposal wells were initially identified in the immediate location of the seismic cluster: WD-K1 (00/16-29-061-04W6/0), WD-K2 (00/14-33-061-04W6/2), and WD-K3 (00/08-33-061-04W6/0; Figure 8a). The three wells started injecting into the Leduc Formation as early as February 2020 and have continued injection operations since. By July 2022, most of the seismicity seems to be contained in a 5 km area around these initially identified wells. A fourth well in the area (WD-K4, 00/05-35-061-04W6/0; Figure 8a), also disposing in the Leduc Formation, started activities in October 2023.

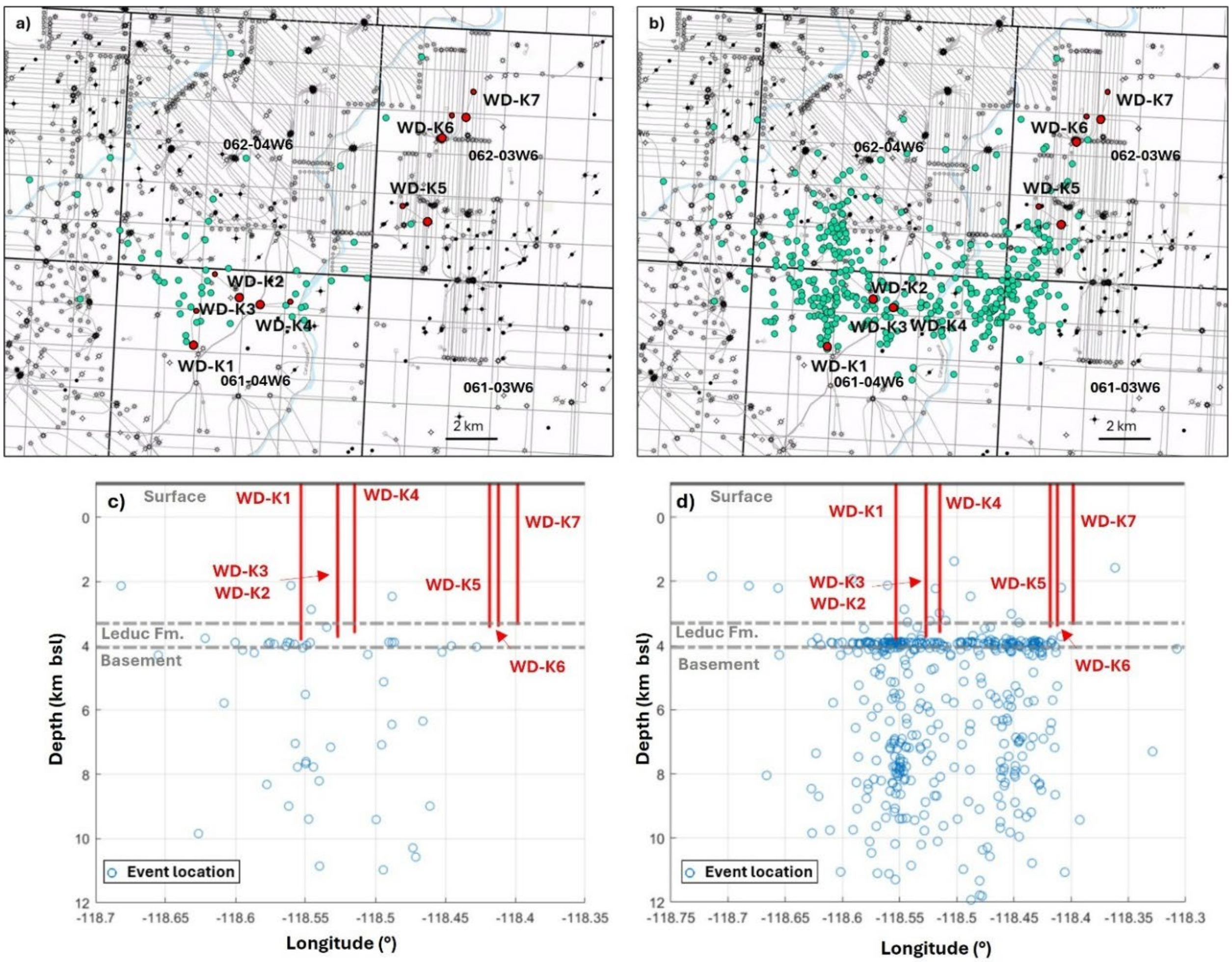


Figure 8. Comparison between the seismicity (green dots) in the Kakwa area, northwestern Alberta, up to (a) July 2022 and (b) August 2023 (Alberta Geological Survey, 2025). Each disposal well (WD-K1–7; injecting into the Leduc Formation) is represented by a large (surface location) and small (bottom hole location) red dot. Notice the expansion of the seismicity towards the east and north. Operational sites in the area, including production wells (black dots) and other oil and gas wells (grey symbols; the thin grey lines represent traces of deviated and horizontal well paths, mostly of multilateral wells in the Montney Formation), are shown (Alberta Energy Regulator, 2025). Depth profiles of seismic events (blue dots) in the Kakwa area up to (c) July 2022 and (d) August 2023 (Alberta Geological Survey, 2025). Abbreviations: bsl, below sea level; WD-K1, 00/16-29-061-04W6/0; WD-K2, 00/14-33-061-04W6/2; WD-K3, 00/08-33-061-04W6/0; WD-K4, 00/05-35-061-04W6/0; WD-K5, 00/10-07-062-03W6/0; WD-K6, 00/15-20-062-03W6/0; WD-K7, 00/12-28-062-03W6/0.

By August 2023, further seismic activity had been recorded, with increasing frequency and reaching events with M_L >3.5 in February 2023. A remarkable characteristic is the expansion of the cluster towards the east, where three other wells disposing into the Leduc Formation were identified: WD-K5 (00/10-07-062-03W6/0), WD-K6 (00/15-20-062-03W6/0), and WD-K7 (00/12-28-062-03W6/0; Figure 8). The disposal activities at these wells started as early as April 2018. Given the occurrence of seismic events near these wells and the disposal activities predating the start of the seismicity, these wells were considered in the evaluation of induced seismicity. Figure 8 shows the distribution of seismic events up to July 2022 (Figure 8a) and August 2023 (Figure 8b), along with the locations of wells in the area. The earthquake catalogue can be found at the AGS Earthquake Dashboard (Alberta Geological Survey, 2025). Many of the other wells shown on Figure 8a and b are production wells or wells where hydraulic fracturing has been conducted. However, the hydraulic-fracturing activities in the area, primarily performed in the Montney Formation, show a weak spatiotemporal correlation with the seismicity. Figure 8 also shows the depth distribution of the earthquakes up to July 2022 (Figure 8c) and August 2023 (Figure 8d). Notice the horizontal lineament around 5 km below the surface, this is likely an artifact resulting from the location process (e.g., the low-velocity zone in the input velocity model).

Figure 9a–d shows the frequency and magnitudes of earthquakes up to July 2022 and up to August 2023, as well as the monthly injection volumes into the Leduc Formation in the area. Notice how the increasing pattern of disposal volumes matches the increasing frequency and magnitude of events. This pattern was further confirmed by cross-correlation analysis (Appendix 1, Figure 14), where a sizeable correlation between disposal activities and seismic events was identified as well as an increase in the correlation between injection rates and seismicity from the up to July 2022 period to the up to August 2023 period (from 0.47 to 0.51 at the zero-month lag).

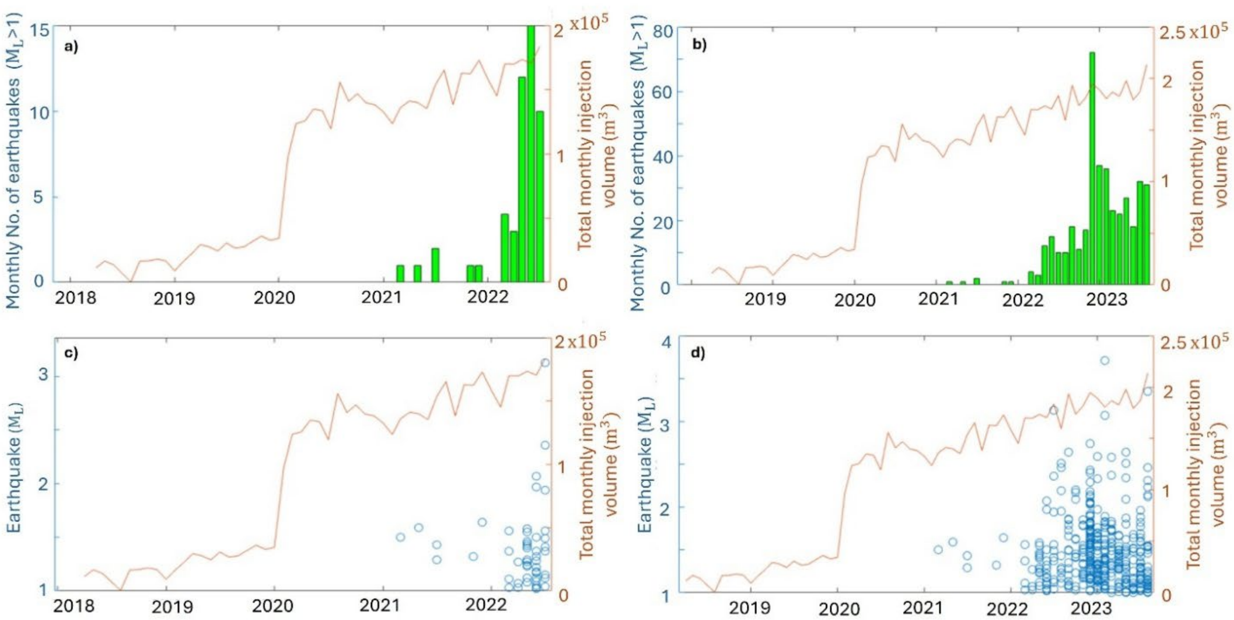


Figure 9. Monthly number of earthquakes (green bars) up to (a) July 2022 and (b) August 2023 and magnitude of seismic events (blue circles) up to (c) July 2022 and (d) August 2023 in the Kakwa area, northwestern Alberta (Alberta Geological Survey, 2025). The orange line shows the monthly injection volumes into the Leduc Formation in the area (Alberta Energy Regulator, 2025).

The seismic events show depths as shallow as 3 to 4 km below surface, proximal to the depths of the disposal operations into the Leduc Formation (around 4.5 km below surface; Figure 8c and d). However, the estimated depths of the mainshocks are observed at lower depths, from 6 to 8 km bsl, which correspond to the Precambrian basement (Figure 8c and d). Figure 10a shows a map view of the locations of the Leduc Formation reef complexes in the area south of Grande Prairie. The disposal activity that has been identified proximal to the Kakwa seismic cluster corresponds to the location of the Simonette reef complex. Other seismic clusters, like the Gold Creek case, are located at the Steep Creek reef complex, whereas the Musreau Lake cluster, with seismicity related to disposal into the Winterburn Group, is situated between reef complexes. Figure 10b shows a geological sketch from a northwest-southeast cross-section. Notice the Kakwa cluster on the right, where the identified disposal activities are injecting in the Simonette reef complex. The hypothetical faults extend from the basement towards shallower formations like the Leduc Formation. The activation of basement-rooted faults is commonly seen in other cases of induced seismicity in Alberta, where evidence of fault displacement (earthquakes) or geological indications of hydraulic conductivity connect shallower industrial activities with deeper events (Schultz et al., 2017; Li et al., 2021).

3.2.1 Application of the Verdon et al. (2019) Questionnaire

The Verdon et al. (2019) questionnaire was applied to the Kakwa earthquake sequence using the information available for two different time periods: up to July 2022 and up to August 2023. Table 3 summarizes the chosen answers. For the first question, option 'c' was chosen for both time periods, as over a decade of seismic monitoring by the AGS had not recorded any events in the area before 2017 (Table 3). However, given the limits of the regional seismological network, this question was given a weight of 0.75 out of 1. Since natural earthquakes with a relatively similar depth have been assumed to have occurred in the broader regional context, option 'd' was also chosen for both time periods (Table 3). The second question refers to the temporal coincidence between the onset of events and industrial activities. Option 'c' was chosen for both time periods, since the events were occurring at the same time as the industrial activity (Table 3). The third question refers to the correlation between disposal volumes and seismicity. There is a good correlation between earthquakes and seismicity using the information available up to July 2022, thus, option 'c' was chosen (Table 3). The correlation becomes stronger over time and given the information available up to August 2023 (see Appendix 1, Figure 14), option 'c' was also chosen (Table 3). The increasing correlation by August 2023 was the final indication in favour of a strong correlation. For both questions 2 and 3, a weight of 1 was given.

For the fourth question, option 'c' was chosen for both time periods (Table 3). From the earthquake catalogues, earthquakes as shallow as 3 to 4 km below surface were identified, they are proximal to the depths of the disposal operations in the Leduc Formation (around 4.5 km deep). Acknowledging the limited coverage of the regional array, the oversimplified 1D input velocity model used for event location, and the associated uncertainties in the depths, a weight of 0.75 was given to the question. For the fifth question, it is clear by July 2022 that the earthquakes are sufficiently close to the activities, given the putative causative mechanism, thus, option 'b' was chosen (Table 3). However, by August 2023, it is clear that the expansion of the seismicity follows the description of option 'c,' where the earthquake loci change/expand with time (Table 3). For this question, a weight of 1 was given, given the good reliability of the epicentral location of the earthquakes. For the sixth question, it is reasonable to elucidate a possible mechanism given the proximal hypocentral location of the events to the disposal activities. For both time periods, option 'b' was chosen (Table 3). It is possible to argue for option 'c' instead (Table 3); however, a conservative approach was taken until a higher-resolution earthquake catalogue, which would better elucidate the link, is available. For this latter reason, this question was given a weight of 0.75. Finally, question 7 was not included since there was a lack of available information regarding the source mechanism of the earthquakes.

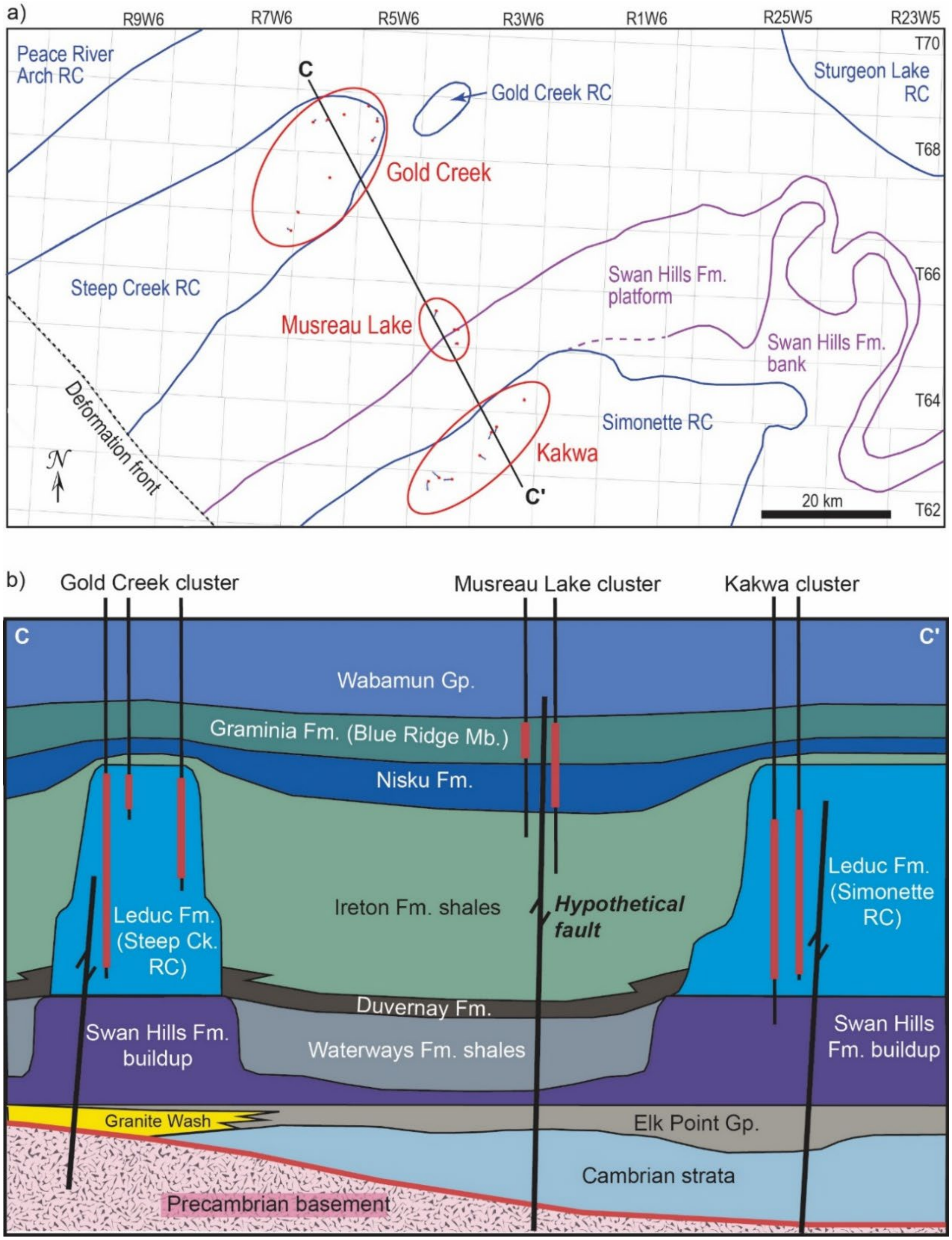
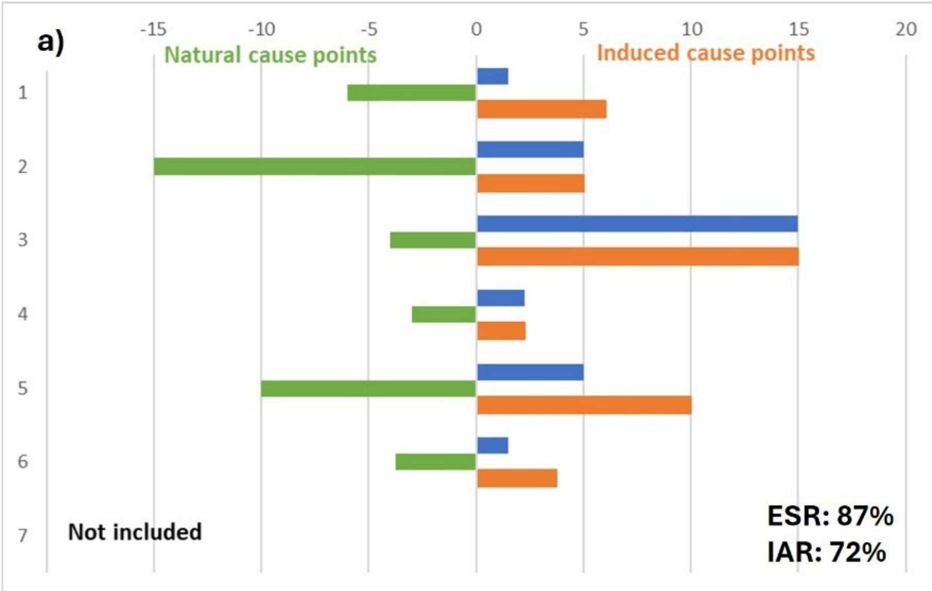


Figure 10. (a) Map view of the Leduc Formation reef complexes (RC; modified from Switzer et al., 1994) and Swan Hills Formation buildups (modified from Wendte and Uyeno, 2005) in the area south of Grande Prairie, northwestern Alberta. The three main seismic clusters in the area, including the Kakwa cluster, are outlined in red. Red dots with blue lines show the location of the disposal wells injecting into the Leduc Formation (Alberta Energy Regulator, 2025). (b) Geological schematic from a northwest–southeast cross-section C-C', location shown in (a). Notice the wells with disposal-related completion perforations (red bars) into the Leduc Formation and the Graminia and Nisku formations (Winterburn Group) and the hypothetical faults extending to the basement. Abbreviation: Cr., Creek.

Table 3. Answers to the Verdon et al. (2019) questionnaire for the Kakwa earthquake sequence, northwestern Alberta, with the information available up to July 2022 and August 2023. Modified from Verdon et al. (2019) © Seismological Society of America. Abbreviation: N/A, not included; Q, question.

Question and Possible Answers	Answer Score	Answer for up to July 2022	Answer for up to August 2023
Q1. Has there been previous (either historical or instrumental) seismicity at the same site, or within the same regional setting?	**Score**	**Evidence weight: 75%**	**Evidence weight: 75%**
a) Earthquakes have previously occurred in the vicinity of the site, with similar rates and magnitudes	-5	No (0 resulting points)	No (0 resulting points)
b) Earthquakes have previously occurred within the same regional setting, with similar rates and magnitudes	-2	No (0 resulting points)	No (0 resulting points)
c) Earthquakes have not occurred at similar rates or magnitudes within the regional setting	5	Yes (3.75 resulting points)	Yes (3.75 resulting points)
d) Past earthquakes occurred at similar depths within the regional setting	-3	Yes (2.25 resulting points)	Yes (2.25 resulting points)
e) Earthquakes are significantly shallower than any past events that have been observed within the regional setting	3	No (0 resulting points)	No (0 resulting points)
Q2. Is there a temporal coincidence between the onset of events and the industrial activities?	**Score**	**Evidence weight: 100%**	**Evidence weight: 100%**
a) The earthquake sequence began prior to the commencement of industrial activity	-15	No (0 resulting points)	No (0 resulting points)
b) The earthquake sequence did not begin until a significant period of time after the cessation of industrial activity	-5	No (0 resulting points)	No (0 resulting points)
c) The earthquake sequence began while the industrial activity was ongoing	5	Yes (5 resulting points)	Yes (5 resulting points)
Q3. Are the observed seismic events temporally correlated with the injection or extraction activities?	**Score**	**Evidence weight: 100%**	**Evidence weight: 100%**
a) The earthquakes are coincident with the industrial activity, but there is minimal correlation	-4	No (0 resulting points)	No (0 resulting points)
b) There is some temporal correlation between the seismicity and the industrial activity	4	No (0 resulting points)	No (0 resulting points)
c) There is a strong temporal correlation between the seismicity and the industrial activity (e.g., between rates of injection and rates of seismicity)	15	Yes (15 resulting points)	Yes (15 resulting points)
Q4. Do the events occur at similar depths to the activities?	**Score**	**Evidence weight: 75%**	**Evidence weight: 75%**
a) Earthquakes do not occur at the same depth, and there is no plausible mechanism by which stress or pressure changes could be transferred to these depths	-4	No (0 resulting points)	No (0 resulting points)
b) Earthquakes do not occur at the same depth, but plausible mechanisms exist by which stress, or pressure changes could be transferred to these depths	2	No (0 resulting points)	No (0 resulting points)
c) Earthquakes occur at similar depths to the industrial activity	3	Yes (2.25 resulting points)	Yes (2.25 resulting points)
Q5. Is there spatial collocation between events and the activities?	**Score**	**Evidence weight: 100%**	**Evidence weight: 100%**
a) Earthquakes are distant from the activities, given the putative causative mechanism	-10	No (0 resulting points)	No (0 resulting points)
b) Earthquakes are sufficiently close to the activities, given the putative causative mechanism	5	Yes (5 resulting points)	No (0 resulting points)
c) If earthquake loci change with time, this change is consistent with the industrial activity, for example, growing radially from a well or shifting in response to the start of a new well	10	No (0 resulting points)	Yes (10 resulting points)
Q6. Is there a plausible mechanism to have caused the events?	**Score**	**Evidence weight: 75%**	**Evidence weight: 75%**
a) No significant pore-pressure increase or decrease occurred that can be linked in a plausible manner to the event hypocentral position	-5	No (0 resulting points)	No (0 resulting points)
b) Some pore-pressure or poroelastic stress change occurred that can be linked in a plausible manner to the event hypocentral position	2	Yes (1.5 resulting points)	Yes (1.5 resulting points)
c) A large pore-pressure or poroelastic stress change occurred that can be linked in a plausible manner to the event hypocentral position	5	No (0 resulting points)	No (0 resulting points)
Q7. Does the source mechanism indicate an induced event mechanism?	**Score**	**Evidence weight: N/A**	**Evidence weight: N/A**
a) The source mechanisms are consistent with the regional stress conditions	0	N/A	N/A
b) Source mechanisms are not consistent with the regional stress conditions, but are consistent with a putative causative mechanism (e.g., thrust faults above a subsiding reservoir)	4	N/A	N/A



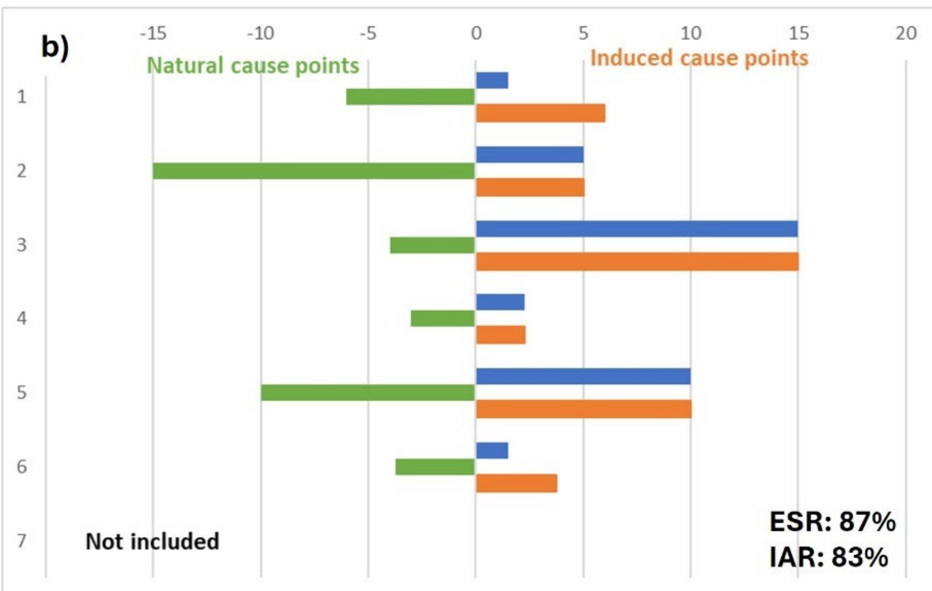


Figure 11. Summary (blue bars) of the evidence strength ratio (ESR) and induced assessment ratio (IAR) for the Kakwa earthquake sequence, northwestern Alberta, using the available information up to (a) July 2022 and (b) August 2023, based on the Verdon et al. (2019) questionnaire. The points are adjusted based on the certainty of data available. The green and orange bars refer to the total amount of points per question that can be achieved, considering the certainty factor.

Figure 11a and b shows a summary of the ESRs and IARs for the Kakwa earthquake sequence for the two different time periods. Using the information available up to July 2022, an ESR = 87% and an IAR = 72% were obtained, suggesting a good amount of evidence and a clear inclination towards induced seismicity. By reanalyzing this sequence using the information available up to August 2023, an ESR = 87% and an IAR = 83% were obtained, suggesting a good amount of evidence and a very strong indication of induced seismicity.

3.2.2 Application of the Foulger et al. (2023) Questionnaire

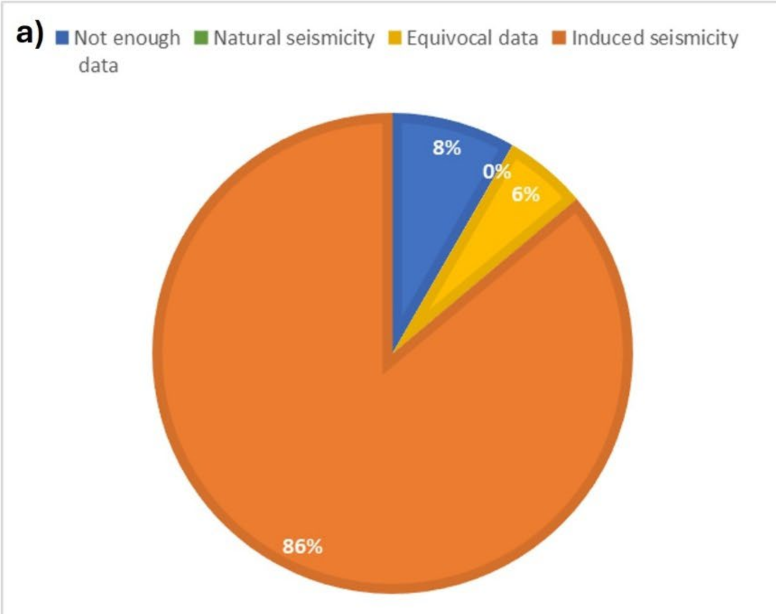
Similar to the previous example, the Foulger et al. (2023) questionnaire was applied to the Kakwa earthquake sequence with the information available for two different time periods: up to July 2022 and up to August 2023. Table 4 shows a summary of the chosen answers. The first question refers to the temporal occurrence of the sequence. Option 'd' was chosen for both time periods, since the PIEs began while industrial activity was substantial (Table 4). Earthquakes in the Kakwa area have been recorded since early 2021, whereas the injection into the Leduc Formation started almost three years prior, in April 2018. The second and third questions refer to epicentral and hypocentral locations, respectively. Option 'd' was chosen for both questions and time periods since the earthquakes are within the likely area of environmental modulation by industrial activity in map view (epicentre) and depth (hypocentre; Table 4).

The fourth question refers to the correlation between volumes and seismicity. For both time periods, option 'd' was chosen since there is a strong temporal correlation between seismicity and disposal volumes (Table 4). It is possible to argue for option 'c', given the available information in July 2022, however, it was considered more appropriate to describe the relationship as strong rather than weak, as proposed by option 'c' (Table 4). The fifth and sixth questions refer to the epicentral and hypocentral locations of the pre-industrial earthquakes. Option 'c' was chosen for both questions and for both time periods (Table 4), since natural earthquakes with a relatively similar depth have been assumed to have occurred in the broader regional context (particularly towards natural seismic sources in the Foothills and the Rocky Mountains, see Reyes Canales and van der Baan, 2022). The seventh question refers to the information on the focal mechanism, however, this information was not available thus option 'a' was chosen (Table 4). The eighth and ninth questions refer to any additional seismic or nonseismic data available to determine the origin of the sequence. For the first time period, seismic information was not available thus option 'a' was chosen (Table 4). For the second time period, some characteristics, like the expansion of the cluster, could be used as seismic data to support induced seismicity, thus, option 'd' was chosen for question 8 (Table 4). Nonseismic data was not available thus option 'a' was chosen for question 9 for both time periods (Table 4).

Figure 12a and b shows a pie chart generated from responses to the questionnaire from Foulger et al. (2023) for the Kakwa earthquake sequence for the two time periods. Using the information available up to July 2022, 86% of the points are inclined towards induced seismicity origin, 8% of the points towards insufficient or not available data, 6% of the points towards equivocal data, and no points towards natural seismicity. The results slightly changed by August 2023, resulting in 89% of the points inclined towards induced seismicity origin, 6% of the points towards equivocal data, 5% of the points towards insufficient or not available data, and no points towards natural seismicity.

Table 4. Answers to the Foulger et al. (2023) questionnaire for the Kakwa earthquake sequence, northwestern Alberta, with the information available up to July 2022 and August 2023. Modified from Foulger et al. (2023). Abbreviation: PIE, potential induced earthquake.

Question	Possible Answers	Points for up to July 2022	Points for up to August 2023
Question 1 PIE-temporal	**Did the PIE sequence onset before, during, or after the industrial activity?**		
	a) Insufficient information available	0	0
	b) The PIE sequence began before the onset of the industrial activity	0	0
Weight of question	c) The PIE sequence began while the industrial activity was minimal or after cessation	0	0
10 points	d) The PIE sequence began while the industrial activity was substantial	10	10
Question 2 PIE-epicentres	**Is there spatial collocation between the PIEs and the likely area of environmental modulation by the industrial activity?**		
	a) Insufficient information available	0	0
Weight of question	b) The PIEs are outside the likely area of environmental modulation by the industrial activity	0	0
100 points	c) The PIEs are peripheral to the likely area of environmental modulation by the industrial activity	0	0
	d) The PIE are within the likely area of environmental modulation by the industrial activity	100	100
Question 3 PIE-hypocentres	**Is there spatial collocation between the PIEs and the likely area of environmental modulation by the industrial activity?**		
	a) Insufficient information available	0	0
	b) The PIEs are beneath the likely volume of environmental modulation by the industrial activity	0	0
Weight of question	c) The PIEs are peripheral to the base of the likely volume of environmental modulation by the industrial activity	0	0
100 points	d) The PIEs are within the likely volume of environmental modulation by the industrial activity	100	100
Question 4 PIE-temporal	**Is there a temporal correlation between the PIEs and specific industrial events?**		
	a) Insufficient information available	0	0
	b) There is little or no temporal correlation between the PIEs and specific industrial events	0	0
Weight of question	c) There is a weak temporal correlation between the PIEs and specific industrial events	0	0
100 points	d) There is a strong temporal correlation between PIEs and specific industrial events	100	100
Question 5 Pre-industrial earthquake epicentres	**Is there evidence for pre-industrial earthquakes at or near the site of the PIEs?**		
	a) Insufficient information available	0	0
	b) Pre-industrial earthquakes occurred at or near the site of the PIEs	0	0
Weight of question	c) Pre-industrial earthquakes occurred only in the wider region around the site of the PIEs	10	10
10 points	d) Pre-industrial earthquakes did not occur at or near the site of the PIEs or in the wider region around it	0	0
Question 6 Pre-industrial earthquake hypocentres	**Is there evidence for pre-industrial earthquakes in the same volumes as the PIEs?**		
	a) Insufficient information available	0	0
	b) Pre-industrial earthquakes occurred at or near the site of the PIEs at similar or shallower depths	0	0
	c) Pre-industrial earthquakes occurred only in the wider region around the site of the PIEs at similar or shallower depths	10	10
Weight of question 10 points	d) Pre-industrial earthquakes did not occur at or near the site of the PIEs or in the wider region around it at similar or shallower depths	0	0
Question 7 Focal mechanism	**Are there focal mechanisms consistent with a natural and/or induced earthquake cause?**		
	a) Insufficient information available	10	10
	b) The focal mechanisms are consistent with the regional stress and not consistent with the proposed induction mechanism	0	0
Weight of question	c) The focal mechanisms are consistent with the regional stress and are consistent with the proposed induction mechanism OR the focal mechanisms are not consistent with the regional stress and are consistent with the proposed induction mechanism	0	0
10 points	d) The focal mechanisms are not consistent with the regional stress and are consistent with the proposed induction mechanism	0	0
Question 8 Other seismic data	**Are there other seismic data to support a natural or induced cause (e.g., swarm, foreshock-aftershock pattern, b-value, total number of earthquakes, radical change in style of seismicity, stress release corresponding to the earthquake magnitude of seismicity)?**		
	a) Insufficient information available	10	0
	b) Other seismic data support a natural origin	0	0
Weight of question	c) Other seismic data are equivocal	0	0
10 points	d) Other seismic data support an induced origin	0	10
Question 9 Other nonseismic data	**Are there nonseismic data that support a natural or induced cause (e.g., direct nucleation effects, precursory surface deformation)?**		
	a) Insufficient information available	10	10
Weight of question	b) Other nonseismic data support a natural origin	0	0
10 points	c) Other nonseismic data are equivocal	0	0
	d) Other nonseismic data support an induced origin	0	0



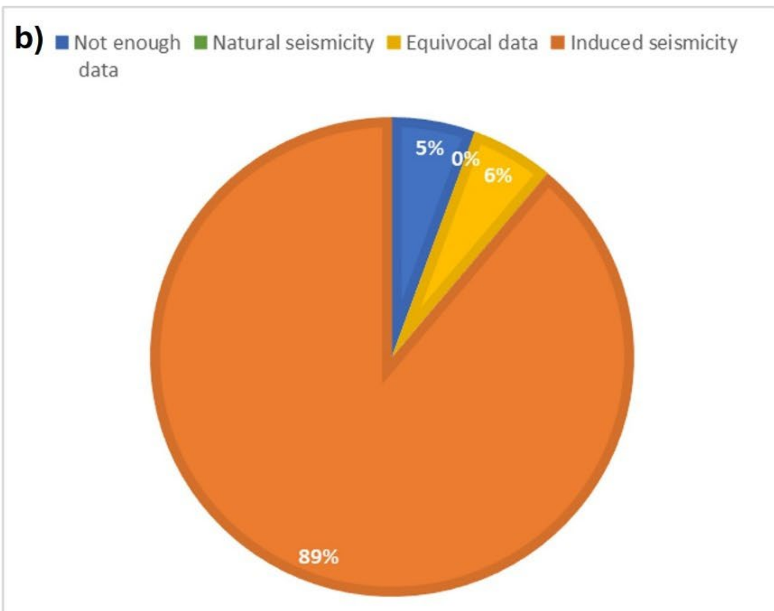


Figure 12. Pie chart generated from all of the responses to the questionnaire from Foulger et al. (2023) using the available data for the Kakwa earthquake sequence, northwestern Alberta, up to (a) July 2022 and (b) August 2023.

4 Discussion

Using evidence-scoring tools (questionnaires) to discern between natural and induced seismicity can be a valuable tool in the initial evaluation and identification of induced seismicity. Although the pioneering criteria from Davis and Frolich (1993) remain valid, questionnaires like Verdon et al. (2019) and Foulger et al. (2023) have been designed to address some of the limitations in the Davis and Frohlich (1993) criteria, as well as provide more sophisticated ways to express the degree of certainty that an earthquake sequence is induced, natural, or ambiguous and more data is necessary. The two case studies with varying levels of complexity were selected to demonstrate the application of these questionnaires and assess their effectiveness as tools for the preliminary evaluation and discrimination of earthquake sequence origins, whether natural or induced. On the one hand, there are less complex cases like the earthquake sequence in the Kakwa region, with initial small-magnitude events and increasing frequency and magnitude of earthquakes over time. After 16 months of data collection from March 2021 to July 2022, when the first M_L >3 event was detected, there was already strong evidence that the cluster was related to disposal activities. On the other hand, there are more challenging cases that require in-depth analysis, like the Reno earthquake sequence with sparse seismicity before the November 2022 events that included the M_L = 5.59 mainshock. When this large earthquake happened, there was ambiguous data about the origin of the sequence, and more information was necessary for a conclusive result.

These two cases illustrate the diverse characteristics that induced seismicity can exhibit, as well as the varying levels of complexity involved in its identification. In some instances, such as the Kakwa case, seismicity begins with small, continuous events, allowing for the determination of the nature of the seismicity over an extended observation period. In contrast, cases like Reno involve initially sparse activity followed by a significant event after several years, requiring advanced data acquisition to enable timely assessment of the cause. Another feature to point out about using these questionnaires is how the conclusion may vary over time, by adding further evidence. For the earthquake sequence near Reno, both questionnaires initially yielded ambiguous results based on the data available up to November 2022. However, the seismic nodal array data up to March 2023 was added to the assessment and the seismic sequence showed clear signs of persistence, then both questionnaires significantly leaned towards an induced seismicity origin. In contrast, for the Kakwa earthquake sequence, both questionnaires strongly favoured an induced seismicity origin based on the available information up to July 2022 and August 2023.

These questionnaires are just one of several tools that seismologists should utilize when determining natural and induced seismicity; a thorough understanding of the geology and the physical processes responsible for the earthquakes is essential. The usefulness of these questionnaires depends on the reliability and availability of the input data and the expertise of the interpreter performing the assessment. Therefore, they should be considered as an initial guide for evaluating induced seismicity, with a clear recognition of their limitations and uncertainties. The results obtained using the Verdon et al. (2019) and Foulger et al. (2023) questionnaires do not aim to quantify the amount of contribution from different operations to seismic activity near the Reno and Kakwa seismic clusters. In the case of the Reno cluster, it is possible that the disposal activities in the Belloy Formation, or even other distant disposal wells (20 km away or more) injecting into the Leduc Formation, could have contributed to the changes in the state of stress in the fault, resulting in seismicity. As noted earlier, accurately determining the extent to which each activity contributed to the fault activation is difficult, particularly due to the limited information available at the time of the mainshock. Based on information available up to March 2023, what is clear, however, is that the disposal operations at WD-R1 show the clearest causation path that leads to fault activation: pore pressure increase from injection into the Leduc Formation that activated basement-rooted faults near the disposal operation. Other operations, such as disposal activities in the Belloy Formation, must rely on unlikely scenarios of hydraulic conductivity to be clearly included as a contributor. Thus, as more data emerge and are thoroughly analyzed over time, they will help to accurately constrain the event's origin. A later study will address how the improved reliability and availability of information will further contribute to a more precise understanding of the event’s cause.

5 Conclusions

In this study, the Verdon et al. (2019) and Foulger et al. (2023) questionnaires were implemented to determine the origin of two earthquake sequences in Alberta: the seismic cluster near Reno, Peace River region, and the seismic cluster in the Kakwa area, south of Grande Prairie. The feasibility of using these evidence-scoring tools (questionnaires) for both cases was also assessed by analyzing the information available for two different time periods to illustrate how the questionnaire responses evolved over time and how they help seismologists in the initial evaluation and identification of induced seismicity. Both questionnaires initially provided ambiguous results for the earthquake sequence near Reno based on the data available up to November 2022, when a mainshock, local magnitude 5.59, was recorded. However, using the available information up to March 2023, which included the acquisition of high-resolution nodal array data, the questionnaires shifted significantly towards an induced seismicity origin, the earthquake depths were properly constrained and persistent anomalous seismicity after the November mainshock was observed. In contrast, both questionnaires strongly suggest an induced seismicity origin early on for the Kakwa earthquake sequence, based on the data available up to July 2022 and August 2023. Both the Reno and Kakwa earthquake sequences are contrasting examples of the different features that induced seismicity can display and the various degrees of challenges in determining induced seismicity that, in some cases, require the acquisition of high-resolution seismological data and additional time to observe the seismicity evolution. These questionnaires address some of the challenges in the pioneering criteria from Davis and Frohlich (1993), providing a framework to include uncertain information and to communicate the levels of ambiguity in the results. However, these two questionnaires should be viewed as initial tools for guiding the assessment of natural versus induced seismicity. Their effectiveness depends heavily on the accuracy of input parameters and the expertise of the interpreter. Crucially, a thorough understanding of the local geology and underlying physical processes is essential for reliable interpretation. While the questionnaires may provide strong indications towards either a natural or induced origin, definitive conclusions cannot be made without a clear understanding of the geological context and earthquake mechanisms involved. Ongoing studies are aimed at addressing this point by integrating more detailed geological and geophysical analyses to support more robust interpretations.

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Appendix 1 – Cross-Correlation Plots

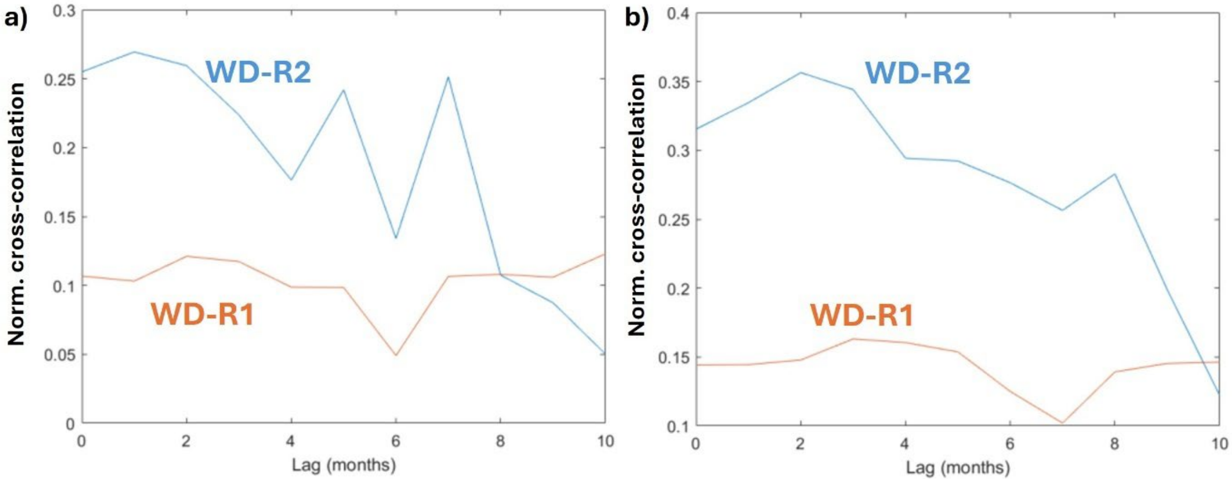

Figure 13. Normalized (Norm.) cross-correlation coefficient as a function of the time lag (month) resulting from cross-correlating seismicity rates and injection rates for the Reno seismic cluster for two different time periods. Notice the increase of the cross-correlation coefficients from the (a) up to November 2022 to the (b) up to March 2023 time period. The WD-R1 refers to the well injecting into the Leduc Formation (00/14-18-082-17W5/0), and WD-R2 refers to the well injecting into the Belloy Formation (00/06-14-082-18W5/0).

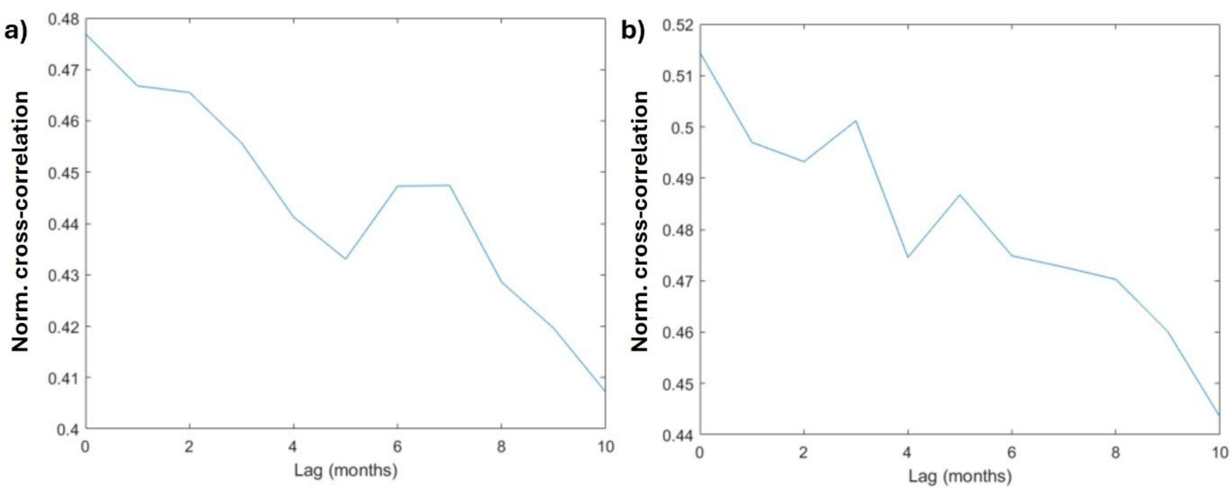

Figure 14. Normalized (Norm.) cross-correlation coefficient as a function of the time lag (month) resulting from cross-correlating seismicity rates and injection rates for the Kakwa seismic cluster for two different time periods. Notice the increase of the cross-correlation coefficients from the (a) up to July 2022 to the (b) up to August 2023 time period. All Leduc Formation disposal wells in the area were included in the analysis (WD-K1, 00/16-29-061-04W6/0; WD-K2, 00/14-33-061-04W6/2; WD-K3, 00/08-33-061-04W6/0; WD-K4, 00/05-35-061-04W6/0; WD-K5, 00/10-07-062-03W6/0; WD-K6, 00/15-20-062-03W6/0; WD-K7, 00/12-28-062-03W6/0).