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Triggering Mechanisms of Induced Seismicity in the Montney Formation: A Comparative Study across different sites

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Summary

Human activities such as hydraulic fracturing can induce seismicity ranging from very low magnitudes to felt events, making it essential to understand the physical processes responsible for fault reactivation. In this study, four hydraulic fracturing sites in the Montney Formation in British Columbia were investigated using an integrated approach to identify the dominant triggering mechanisms associated with individual seismic clusters. Seismic events were first grouped using statistical clustering techniques. Most clusters were activated by pore pressure diffusion from injections, while others indicate fluid migration through high-permeability pathways that enabled rapid fault activation. In Projects B and D, static stress transfer from larger-magnitude events and anomalous structures redistributed stress and triggered seismicity up to ~2.1 km from the source, creating a positive Coulomb failure in the receiver faults. Distance–time analysis further shows that seismicity in the Upper Montney exhibits higher apparent diffusivity between (0.75–6.10 m²/s) and increased event density compared to the Middle and Lower Montney, consistent with enhanced fracturing and fluid mobility. Overall, the results highlight the complexity of induced seismic triggering mechanisms within the formation.

Workflow

To investigate the triggering mechanisms of induced seismicity associated with hydraulic fracturing in the Montney Formation, an integrated approach combining statistical clustering, spatiotemporal analysis, geomechanical modeling, and rock geomechanics was employed. Seismic events were first grouped using a two-stage clustering strategy. Density-Based Spatial Clustering of Applications with Noise (DBSCAN) was applied to event locations and focal mechanism parameters to identify primary clusters while excluding noise. Larger clusters were subsequently refined using a Gaussian Mixture Model (GMM) to resolve overlapping subclusters and complex fault geometries.

Distance–time (r–t) plots were then constructed for each cluster relative to injection stages to evaluate whether seismicity was controlled by fluid migration processes. These plots were used to estimate apparent hydraulic diffusivity and to distinguish between fracture growth, pore pressure diffusion, fault reactivation, and stress transfer mechanisms.

The stress and pore-pressure conditions required for cluster activation were assessed using Mohr–Coulomb failure analysis, with stresses resolved onto fault planes using the tensor method. Semi-analytical modeling following Rudnicki (1986) was applied to quantify pore pressure diffusion and poroelastic stress changes associated with hydraulic stimulation, with injection rate, hydraulic diffusivity, and rock mechanical properties systematically varied across different formations and stimulation stages. When modeled pressure and stress changes were insufficient to explain activation, focal mechanism solutions were examined to identify pre-existing fracture networks or high-permeability pathways, such as fracture corridors, capable of facilitating rapid fluid migration. These scenarios were evaluated using analytical flow models assuming an idealized infinite stripe geometry (Hsieh and Bredehoeft,1981)

If neither fluid diffusion nor fracture-controlled flow could account for the observed seismicity, static stress transfer was investigated by calculating Coulomb stress changes using Coulomb 3.3 induced by hydraulic fractures or significant seismic events (Toda et al.,2011). Finally, well log data were analyzed to assess rock mechanical properties and in-situ stress variations, providing insight into anomalous seismic behavior and spatial offsets between injection zones and seismic clusters.

Results and Conclusions

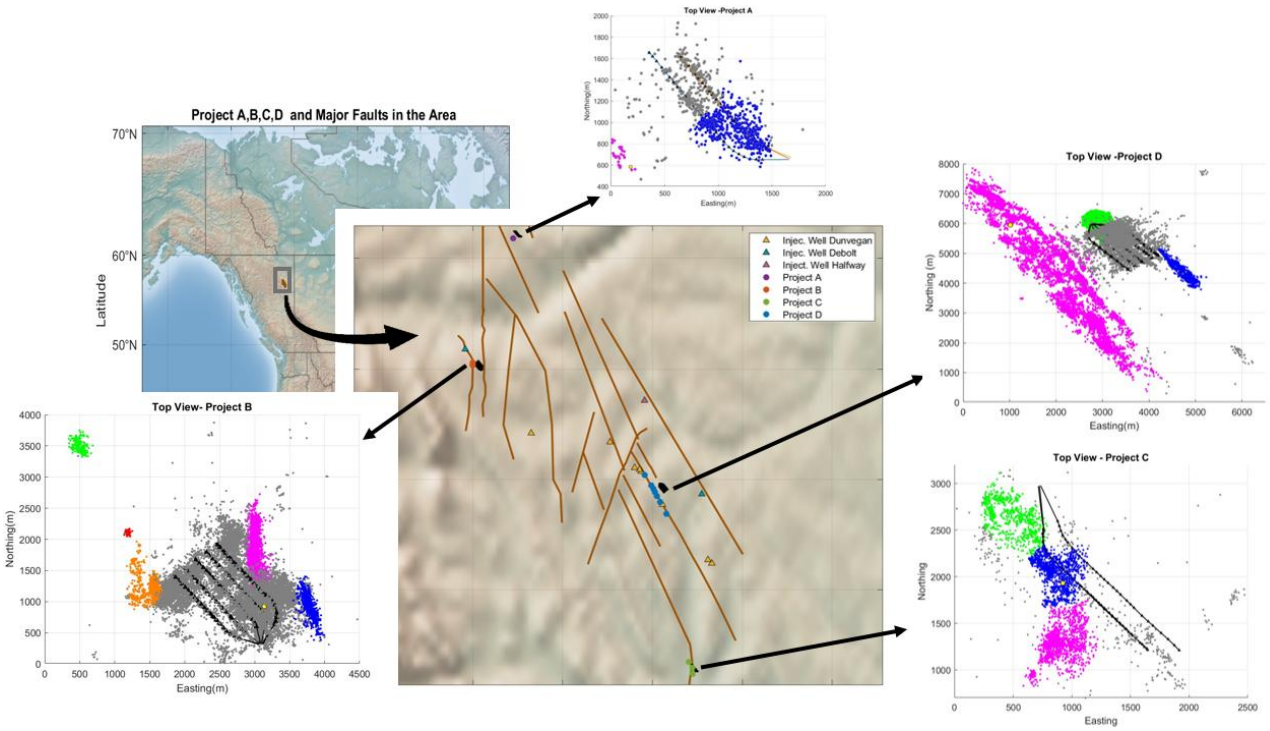


Figure 1: Location of the study area in northeastern British Columbia. Major regional faults, obtained from producer reports, are shown in brown. The triangle denotes the wastewater injection well that predates the hydraulic fracturing (HF) wells. Individual HF sites are displayed with their respective seismic clusters. Major clusters are highlighted in magenta, blue, green, orange, and red, while grey clusters were excluded from the triggering mechanism analysis. The yellow dot in each site represents the larger Magnitude event Mw 1.71, 2.9, 2.36, and 4.6 in Projects A,B, C, and D, respectively.

Project A recorded the fewest seismic events among the four sites, with a maximum magnitude of Mw 1.71. Seismicity was confined to two clusters and was primarily driven by pore pressure diffusion and poroelastic stress transfer. These mechanisms increased pore pressure and altered the stress state, effectively reducing the normal stress acting on pre-existing faults and thereby destabilizing the clusters to trigger seismic activation. No evidence was found for fault-controlled fluid flow or static stress transfer influencing seismicity at this site.

In Project B, cluster green, located 2.3 km from the injection wells, this could likely be influenced by a neighboring well activated approximately one year before Project B. Modeling indicates that

an apparent diffusivity of ~0.05 m²/s was sufficient to reactivate this cluster. Additionally, the magenta cluster was initiated during injection in the Upper Montney Formation but is located between the Lower Montney and Debolt formations. Neither pore pressure diffusion nor poroelastic stress changes could reach this depth within the observed time window. However, the presence of abundant fractures in this interval suggests that downward fluid migration through an interconnected fracture network elevated stresses sufficiently to trigger seismicity in this cluster. Notably, seismicity was observed in the Doig Formation (blue cluster), approximately 400 m above the injection zone, where neither pore pressure diffusion, poroelastic stress changes, nor fracture-mediated fluid flow could account for the rapid activation. Instead, static stress transfer from the largest-magnitude event (Mw 2.9), which occurred about 40 minutes earlier, likely triggered seismicity within the mechanically brittle Doig interval. This mechanism operates much faster than pore pressure diffusion or poroelastic deformation and can rapidly alter stress conditions even above the injection formation.

Project C shows significant seismicity concentrated along major faults, with a maximum magnitudes Mw 2.36. These events were primarily activated by pore pressure and poroelastic stress changes under relatively low stress perturbations.

Project D contains three major clusters, all of which were activated by stress transfer associated with an anomalous structure located between wells. Spatial and temporal analyses indicate that this structure was activated first, followed by increased seismicity in surrounding clusters. Coulomb stress modeling confirms positive stress changes in these clusters, consistent with static stress transfer. Across all sites, multiple triggering mechanisms were identified, with anomalous structures and stress interactions playing a critical role in fault activation. Only Project B produced a larger-magnitude event, suggesting a closer proximity to critical stress conditions compared to the other sites.

Overall, the distance–time analysis of the project shows that seismicity in the Upper Montney exhibits substantially higher apparent hydraulic diffusivity up to 6.10 m²/s and a greater number of events compared to the Middle and Lower Montney. The Upper Montney is characterized by slightly lower minimum horizontal stress and higher gamma-ray variability, consistent with enhanced fracturing and fluid mobility.

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