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If I could turn back time: Is seismicity generated after a critical state transition during sustained water disposal?

Rebecca O. Salvage, Carolyn M. Furlong and David W. Eaton
Department of Geoscience, University of Calgary

Summary

Water Disposal (WD) in western Canada is not as prevalent as hydraulic fracturing or other types of resource development, but still has the ability to generate felt seismicity. However, the temporal and spatial correlation between seismicity and disposal can be difficult to determine, with significant offsets often occurring, making a direct correlation between the two ambiguous. Furthermore, unlike during hydraulic fracturing experiments, changes in the operational conditions during disposal (e.g., injection timings and pressures) do not always correlate with seismicity; in some cases, injection can occur uninhibited for a number of years before a change in the rate of seismicity is detected. It is possible that the late onset of seismicity relates to a critical state transition within the subsurface from predominantly aseismic slip to a regime dominated by seismic energy release, caused (and sustained) by injection into the subsurface. Alternatively, it is possible that the injection of fluid may generate a pressure diffusion front that moves slowly away from the point of injection, the rate of which is controlled by reservoir characteristics. Here, we explore a number of recent cases of potential injection induced seismicity sequences related to water disposal in western Canada, which appear to exhibit large temporal offsets between the initiation of fluid injection and (possible) related seismicity.

Water Disposal in Western Canada

Western Canada is well known for its resource development activities, which have rapidly increased in size and frequency over the past few decades with the introduction of multi-stage fracturing and horizontal drilling, allowing previously uneconomic reserves to be exploited (e.g., Atkinson et al., 2016). As such, the number of hydraulic fracturing (HF) wells drilled in the Western Canadian Sedimentary Basin (WCSB) has increased with over 40,000 wells operational between 2000 and 2020 (Rodríguez-Pradilla et al., 2022). Potentially related to this is the apparent increase in felt seismicity (typically > M3) in the WCSB in recent years (Babaie-Mahani et al., 2020, Salvage and Eaton, 2022). With an increase in HF, there has also been a significant increase in the need to dispose of wastewater from such activities (Alessi et al., 2017). In general, the process of disposal of such water (herein termed water disposal (WD)), involves continuous pressurized injection into saline aquifers (formations that have high porosity and permeability) surrounded by impermeable formations, to contain the water (Walsh and Zoback, 2015).

Seismicity associated with WD has become more prominent in the public eye following several felt events, in particular in the United States (e.g., the Mw 5.7 Prague, Oklahoma earthquake in November 2011 (Keranen et al., 2013)). Furthermore, it is hypothesized that the likelihood of inducing felt seismicity may be greater for WD than it is for HF operations, primarily due to the sustained injection pressures over long periods of time that can lead to extensive pressure perturbations at depth (Walters et al., 2015). The high injected volume of water is thought to cause slip on nearby faults as the pore pressure rise causes the lowering of effective normal stress

(Sibson, 1992; Byerlee, 1993; Zoback, 2010) or through aseismic slip (Cornet et al., 1997), in similar processes theorized for generating seismicity due to HF.

However, the number of WD wells in the WCSB is substantially lower than the number of HF operations, and as such, much of the disposal in Western Canada has reported limited seismicity. For example, between January 2020 and April 2022, 247 horizontal HF wells were operational in the Kiskatinaw area of British Columbia, compared to only 37 WD wells (Salvage and Furlong, 2022). There were two notable exceptions to this where WD is the sole resource development activity in the area: Seismicity in the Cordel Field (Schultz et al., 2014) and seismicity close to Musreau Lake (Li et al., 2021; Yu et al., 2021b), both in west central Alberta. Direct correlations between known disposal and ongoing seismicity in other regions (e.g., close to Fort St. John, BC) are ambiguous, at best, due to the proximity of ongoing HF operations (Salvage and Eaton, 2021). Additional difficulties arise in assessing seismicity associated with WD in the WCSB since there appears to be significant temporal (years) and spatial (km) offsets between the injection of fluid and the generation of earthquakes (Horner et al., 1994; Schultz et al., 2014), even in areas where a direct correlation is assumed.

Recent Seismicity in Alberta

Natural seismicity in Alberta is rare, as prior to resource development Alberta was seismically quiet with only a few felt events detected, thought to be related to the formation of the Rocky Mountains and the redistribution of stress on subsurface geological faults (e.g., Lamontagne et al., 2008). Distinguishing between natural and induced events is an ongoing area of research, but typically relies upon accurate depth estimates, source parameter estimations (e.g., stress drops), as well as a detailed understanding of the injection parameters and history in the area (e.g., Zhang et al., 2016).

Small magnitude seismicity ($M_L < 2$) began in west central Alberta in 2016, potentially related to the exploration of condensates and natural gas liquids (Pawley et al., 2018; Li et al., 2022). Since mid-2018, WD has become the primary operation in this area, with a potential correlation to an increase in seismicity: between 2016 and 2022, over 4000 seismic events were detected on a private 8 station array, with 90% occurring since August 2019. Furthermore, the largest event occurred in the middle of this current sequence, a M_L 3.9 in June 2020, although several events of $M_L > 3$ have occurred since August 2019. The close proximity of this seismicity to 4 active WD wells suggests an apparent correlation, with a temporal offset of >12 months between injection initiation and subsequent significant seismicity.

More recently, a sequence of seismicity beginning in November 2022 in northern Alberta (close to Peace River) produced a M 5.3 mainshock event, with several significant fore- and aftershocks. It is unclear as to whether this sequence is natural or induced: fluid injection has occurred in the area, beginning over a decade ago, with no significant changes to operational parameters in recent years. However, the immediate epicentral region has been historically quiescent, until now. An aftershock sequence of >200 events is still ongoing at the time of writing (February 2023).

Evidence of a Critical State Transition

The idea of a continuum between aseismic (stable sliding) and seismic (event nucleation) slip is not new, however the mechanisms that may cause a shift between these two continuum end-members is still not fully understood. The transition from aseismic to seismic nucleation could relate to dynamic fault weakening (Garagash and Germanovich, 2012), static stress transfer (Wei et al., 2015; De Barros et al., 2020), the concentration of shear stress at the edges of an aseismic slip region (Wynats-Morel et al., 2020), or some combination of these. Here, we use the term “critical state transition” to mark this change as the point when critically stressed faults and/or fractures become seismogenic.

Detecting aseismic processes is inherently difficult. It has been hypothesized that repeating seismicity may be one indicator of aseismic creep since repeating events are generated by the repeated rupture on a single fault patch though the reduction of normal stress due to fluid pressure, which may lead to slow slip (Nadeau and McEvilly, 1999; Sammis and Rice, 2001; Uchida and Burgmann, 2019; Hatch et al., 2020). Furthermore, changes in the characteristics of seismicity within a seismic sequence (e.g., significant temporal changes, changes in source characteristics) may be indicative of aseismic phenomena. Recently, Yu et al. (2021a) suggested that the source characteristics of hybrid waveforms identified in injection environments are identical to those seen in plate boundary fault transition zones (known as slow earthquakes or episodic tremor and slip, Beroza and Ide, 2011; Kirkpatrick et al., 2021) and in volcanic environments (e.g., Chouet, 1996; Bean et al., 2014; Denlinger and Moran, 2014). Hybrid waveforms appear to have broader P and S-phase pulses and coda with a lower frequency content than expected for seismic events and may represent the transition between aseismic and seismic slip (Yu et al., 2021a).

The temporal evolution of seismicity and its relationship to injection parameters in both case studies suggests evidence of a potential critical stress change in the subsurface. In west central Alberta, water injection began in 2018, with limited seismicity despite significant changes in injection volumes. However, in August 2019, a definite change in the seismicity rate is observed with a larger daily event count and an increase in the number of events with larger magnitude (>M_L 3). After August 2019, there is also a potential increase in the frequency content of detected waveforms, which may be indicative of a change towards seismogenic processes (e.g., Lahr et al., 1994; Buurman and West, 2010). Additionally, there is some evidence of repeating seismicity within this sequence. We plan to extend our analysis into this sequence to search for tremor-like events, which may be diagnostic of the critical transition that we hypothesize.

Additional evidence that a critical stress change may occur with a temporal (and spatial) delay to fluid injection in the subsurface comes from recent seismicity near Peace River, Alberta. The area has been historically seismically quiet, but with constant significant fluid injection. It is still unclear as to whether the seismicity observed here was induced or actually of natural origin, and we plan to further our investigations into the sequence to include seismic noise analysis to better constrain the subsurface, as well as the identification of any possible repeating seismicity.

Conclusions

Water disposal into the subsurface is often associated with seismicity, however this seismicity typically appears offset in time and space from the point of injection. Here, we investigate several recent sequences of seismicity in Alberta that may provide evidence of a critical state transition in the subsurface; a point at which processes evolve from aseismic to seismic. We search within each of these sequences for evidence such as: 1) temporal changes in the rates of seismicity; 2) temporal changes in the frequency content of seismicity; 3) temporal changes in ambient noise characteristics; 4) repeating seismicity; and 5) evidence of tremor-like signals. Temporal changes in both ambient noise and frequency content of waveforms are often extremely subtle, however combined with other lines of evidence may give our conclusions more confidence. Evidence of this critical state transition is observed in a seismic sequence in west central Alberta between 2018 and 2022, with a distinct change in the temporal rates of seismicity. Prior to this change, much of the deformation in the subsurface was aseismic with limited associated seismicity. Sustained water injection in the area allows the continuation of the seismic sequence, despite a lowering of the injection rates. A second sequence of seismicity near to Peace River, Alberta beginning in 2022 is also under investigation to detect this phenomena.

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