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Mechanisms of Post-Hydraulic Fracturing Induced Seismicity

Shawn C. Maxwell and Ninoska Amundaray
Ovintiv

Summary

Magnitude-based traffic light protocols are widely implemented and have proven effective for managing induced seismicity and mitigating events of concern. These systems adjust operations when seismicity exceeds predefined magnitude thresholds, reducing the likelihood of escalation. Although inherently reactive, traffic light protocols remain central to regulatory frameworks governing induced seismicity in oil and gas development.

During hydraulic fracturing, real-time seismic monitoring allows operators to halt fracture stages early or modify subsequent plans when seismicity approaches critical thresholds, particularly where hydraulic connectivity to seismogenic structures is suspected. A key limitation, however, is the reduced effectiveness of these protocols for seismicity that occurs after injection has ceased. Proactively reducing seismic hazard during active operations may also lower the probability of post-injection events. Here we categorize the types of post-injection seismicity observed during hydraulic fracturing, evaluates associated hazards, and assesses available management strategies. Case studies illustrate the range of mechanisms driving post-injection seismicity and highlight the diverse operational outcomes.

Seismicity induced by hydraulic fracturing often originates from pressure activation of pre-existing, preferentially oriented faults. Typically, seismic activity initiates during injection and declines rapidly once the stage concludes, resulting in seismicity that is concurrent with the operation (see Figure 1). However, fracture propagation and pressure dissipation may continue post-injection, occasionally resulting in additional delayed seismic events. Cross-well strain monitoring via fiber optics has revealed similar post-fracturing growth, which, although less frequent, can lead to elevated seismic rates and magnitudes shortly after injection. As subsurface pressures relax following cessation of pumping, the probability of pressure-driven seismicity diminishes. These induced responses parallel the microseismicity patterns commonly used to image hydraulic fracturing processes.

In certain cases, fault activation can also trigger ongoing aftershock sequences, with seismicity rates and magnitude probabilities following power-law decay patterns similar to those seen in tectonic earthquakes (e.g., the classical Omori's law). The duration of aftershock activity can vary, resulting in examples where aftershocks may also continue after injection is completed as structures equilibrize.

Together, this basic type of near concurrent seismicity responses appear to be most common, with activity concurrent with or slightly delayed after hydraulic fracturing possibly with diminishing

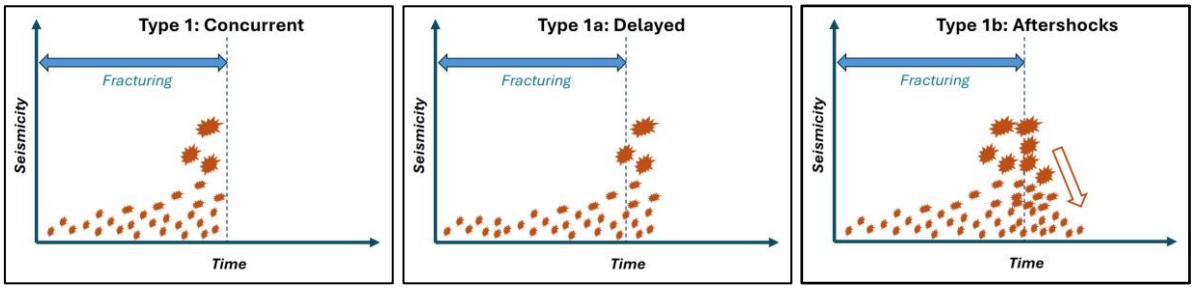


Figure 1. Conceptual description of the most common of post hydraulic fracturing seismicity, concurrent (left), delayed (middle) and continued aftershocks (right).

activity continuing with aftershock equilibration. Nevertheless, traditional traffic light protocols during the operation should effectively manage this concurrent activity.

After injection ceases, delayed latent seismic activity may persist, although both its probability and intensity should diminish over time (see Figure 2). These events typically exhibit magnitudes lower than those observed during the injection phase. These latent events will follow standard frequency-magnitude relations and should be comparable to the largest event detected during the operation. However, larger events may be statistically possible and may also result in additional aftershock activity. Traditional traffic light protocols should also effectively manage this latent activity, provided that seismicity was effectively managed during the operation.

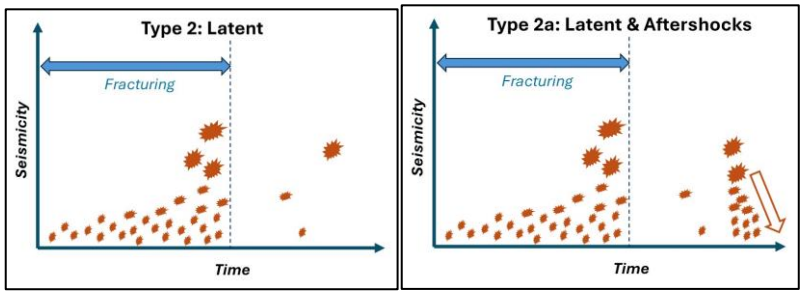


Figure 2. Conceptual description of latent seismicity, isolated events (left) and scenario of continued aftershocks (right).

A more operationally relevant class of post-injection seismicity arises when additional activation energy is introduced into seismogenic structures. Following hydraulic fracturing, stage isolation plugs are typically drilled or milled out before production commences. This process can create varying pressure regimes along the wellbore, occasionally inducing temporary fluid flow. Reactivation sequences—where seismicity temporarily resumes—have been observed during plug drill-out, particularly near sensitive seismogenic faults (see Figure 3). Similarly, the onset of

flowback operations can sometimes trigger renewed seismicity. These events are likely linked to pressure transients, flow changes, and possible poroelastic stress relaxations.

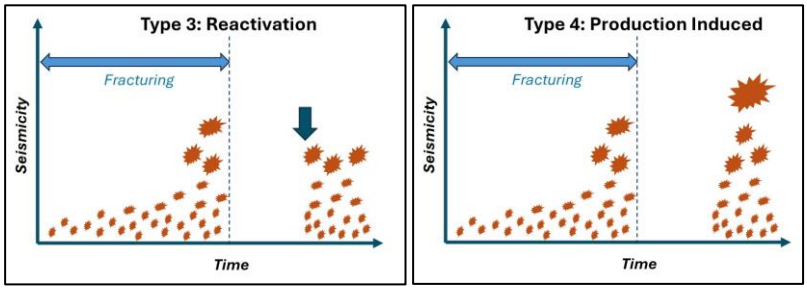


Figure 3. Conceptual description of seismicity associated with reactivation from additional operations (left), production induced (right).

Dissolvable plugs are sometimes used to facilitate re-entry into wells with casing deformation (potentially due to slip), but their variable dissolution times can also lead to delayed seismicity during flowback, associated with pressure differentials. Additionally, if wells are shut in during production, seismicity on previously activated structures may temporarily restart, possibly due to water hammer effects. Notably, seismic events from short-term reactivation during drill-out, flowback, or shut-ins are generally consistent or lower in magnitude than those observed during initial fracturing. It is possible that traffic light protocols implemented during injection also help manage these types of post-injection seismicity.

In contrast, a final category of post-injection reactivation involves mechanisms that can produce seismic events with rates and magnitudes exceeding those observed during active fracturing. These rare occurrences are typically driven by additional activation of energy imparted to seismogenic structures during operations. One notable mechanism is the interaction between hydraulic fracturing and disposal injection in adjacent wells—both processes are independently associated with induced seismicity, and their combined effects can further elevate seismic hazard. If disposal injection rates increase or if disposal-related pressures at seismogenic faults rise sufficiently, reactivation with larger magnitudes may result.

Other rare instances of high-magnitude events have been attributed to alternative mechanisms, such as continued fault activation initiated during fracturing that persists into the production phase, with near-well drainage leading to poroelastic unloading of overpressured structures. Additional mechanisms, including production-related poroelastic effects, may also contribute to such events, though fortunately such scenarios appear to be infrequent in practice.

In summary, hydraulic fracturing-induced seismicity predominantly occurs during the injection period, affirming the effectiveness of traffic light protocols for risk management. Post-injection seismicity can be classified into several categories:

- Events confined to the injection period
- Latent or relaxation events occurring shortly after injection ends
- Reactivation triggered by operational activities such as drill out, flowback, or shut-in

- Reactivation resulting from additional external injection
- Reactivation due to poroelastic triggering

Latent events and aftershock sequences may persist, but their probability and intensity decrease as seismogenic structures equilibrate. Operationally induced reactivation typically produces lower-magnitude events compared to initial injection. Rare cases of reactivation from external injection such as disposal or poroelastic effects may yield larger magnitude events, underscoring the importance of mechanistic classification for hazard assessment and protocol optimization.