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# Two decades of research on injection-induced seismicity: What have we learned?

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## Summary

Injection-induced seismicity – earthquakes triggered by anthropogenic fluid injection into the subsurface – has been well documented for over half a century, including associations with hydrocarbon production. Yet, the past two decades have witnessed an explosion of research on this topic, commencing with seminal work on the relationship between injection, pore-pressure diffusion and induced seismicity. At about that time, it was recognized that induced seismicity poses a serious risk for enhanced geothermal systems (EGS), leading to the introduction of traffic-light systems for use as reactive-control protocols for operations. In the early 2010s, growing realization of the scale and scope of induced seismicity linked to massive saltwater disposal (SWD) in the U.S. midcontinent provided the impetus for considerably expanded research activity. Scientific debate ensued over the potential for hydraulic fracturing, as well as gigatonne-scale carbon capture and storage (CCS), to trigger felt earthquakes. In the case of hydraulic fracturing, it is now well established that the risk of induced seismicity is significant, with notable published examples in North America and China. Basic screening tools have been developed, and widely deployed, to aid in the assessment of fault slip potential, but exhaustive mapping of potentially seismogenic fault systems remains a challenge even using modern 3D seismic data. Building on advancements in artificial intelligence, the seismological community has adapted machine learning methods for use in basic processing of continuous data from seismograph networks as well as to test hypotheses for intrinsic geological susceptibility to fault activation to better explain the patchy nature of seismic activity in unconventional hydrocarbon fairways. There have been debates about the relative importance of various triggering mechanisms, such as direct pore-pressure effect on fault strength, as well as variations in poroelastic stress that modify fault loading conditions. Out of this has emerged a recognition that slow (aseismic) fault slip could also play an important role. Vigorous scientific debates have focused on controls on the magnitude of injection-induced earthquakes, such as net injected volume and injection rate.

What have we learned from the past several decades of research, and what challenges remain? *In situ* measurements of pore pressure using downhole gauges have reasserted the importance, and large spatial extent, of elevated pore pressure within disposal zones. Traffic light systems have been widely adopted by regulators, but with remarkable inter-jurisdictional variability in response thresholds. The advent of risk-based and adaptive approaches for traffic light systems offers significant promise. New monitoring methods, including satellite interferometric synthetic aperture radar (InSAR) and distributed acoustic sensing (DAS), are promising approaches for the detection of aseismic processes that could be important, including for related hazards such as casing deformation. In the context of the energy transition, the advent of competing uses for pore space arising from growth of EGS, carbon capture and storage (CCS), underground gas storage, saltwater disposal (SWD) and extraction of critical minerals from brines, poses additional challenges for understanding cumulative effects of these operations for induced seismicity.