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Statistical mechanics-based forecasting of induced seismicity within the Groningen gas field

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Geological faults may fail and produce earthquakes due to external stresses induced by hydrocarbon recovery, geothermal extraction, CO₂ storage or subsurface energy storage. The associated hazard and risk critically depend on the spatiotemporal and size distribution of any induced seismicity. The observed statistics of induced seismicity within the Groningen gas field evolve as non-linear functions of the poroelastic stresses generated by pore pressure depletion since 1965. The rate of earthquake initiation per unit stress has systematically increased as an exponential-like function of cumulative incremental stress over at least the last 25 years of gas production. The expected size of these earthquakes also increased in a manner consistent with a stress-dependent tapering of the seismic moment power-law distribution. Aftershocks of these induced earthquakes are also observed, although evidence for any stress-dependent aftershock productivity or spatiotemporal clustering is inconclusive.

These observations are consistent with the reactivation of a mechanically disordered fault system characterized by a large, stochastic prestress distribution. If this prestress variability significantly exceeds the induced stress loads, as well as the earthquake stress drops, then the space-time-size distribution of induced earthquakes may be described by mean field theories within statistical fracture mechanics. A probabilistic seismological model based on these theories matches the history of induced seismicity within the Groningen region and correctly forecasts the seismicity response to reduced gas production rates designed to lower the associated seismic hazard and risk.