Peer reviewed:

Science 354 (6318), 1380-1381, DOI: 10.1126/science.aal2584

Title:

Understanding induced seismicity

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Publication date:

12-2016

Copyright information:

GEOPHYSICS

Understanding induced seismicity

Observational data sets provide a clearer picture of the causes of induced seismicity

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Hydraulic fracturing at the Bakken Formation in North Dakota. A mixture of water and fracking fluids are pumped into the ground.

Fluid injection–induced seismicity has become increasingly widespread in oil- and gas-producing areas of the United States (*1*–*3*) and western Canada. It has shelved deep geothermal energy projects in Switzerland and the United States (*4*), and its effects are especially acute in Oklahoma, where seismic hazard is now approaching the tectonic levels of parts of California. Unclear in the highly charged debate over expansion of shale gas recovery has been the role of hydraulic fracturing (fracking) in causing increased levels of induced seismicity. Opponents to shale gas development have vilified fracking as directly responsible for this increase in seismicity. However, this purported causal link is not substantiated; the predominant view is that triggering in the midwestern United States is principally a result of massive reinjection of energy-coproduced wastewaters. On page 1406 of this issue, Bao and Eaton (*5*) identify at least one example of seismicity developed from hydraulic fracturing for shale gas in the Alberta Basin.

Energy supply in the United States has changed dramatically over the past decade. In an energy-hungry world, the shale gas revolution has been heralded both as salvation and as damnation. This position has resulted from unlocking the massive store of gas and oil held in deep, ultralow-permeability shale reservoirs. The successful development of both horizontal drilling and massive hydraulic fracturing has been key to foment this revolution.

On the positive side, this new and abundant supply of gas and liquid hydrocarbons has contributed to a sea change in the U.S. energy outlook, with North America effectively becoming energy-independent (*6*). On the downside, some identify gas-for-coal substitution as only deferring the inevitable hard choice of transitioning from fossil fuel to sustainable energy, noting the impact of cheap gas in impeding penetration of true renewables into the marketplace (*7*). Concerns about rural industrialization, fears of the impact on groundwater resources, dangers inherent in surface transportation of fracturing water and hydrocarbons, the proliferation of pipeline networks, and risks of induced seismicity have all fueled the debate.

Part of this debate, on the causality of induced seismicity, is informed by the analyses of Shirzaei *et al.* (*8*) and by Bao and Eaton (*5*). Their treatments of observational data specifically address the role of massive wastewater injection in triggering seismicity (*8*) and whether the much smaller injections involved in hydraulic fracturing (*5*) may have similar impact.

Induced seismicity in the midwestern United States has grown lockstep with the increase in coproduced waters pumped from near-exhausted conventional oil reservoirs. Disposal of the sometimes four barrels or so of brine produced for every single barrel of oil is typically achieved through reinjection into deep saline aquifers (see the figure). The resulting inflation of deep saline aquifers is the principal, obvious culprit for increased seismicity. Increased fluid pressures reduce the strength of faults transecting the disposal aquifers, which may already be on the point of tectonic reactivation. However, the evidence is often circumstantial and equivocal.

By contrast, Shirzaei *et al.* (*8*) provide a direct link between observations of seismicity and wastewater injection with constraints on surface deformation derived from InSAR (Interferometric Synthetic Aperture Radar). These observations allow the authors to match a straightforward model for the elastic inflation of the porous, disposal aquifer to the deformation signature of uplift at the surface. Predictions of the fluid injection–induced changes in stress causing the surface deformation are then combined with a model of fault failure to infer the observed seismicity. The constraint afforded by the InSAR-measured deformations is the key to establishing causality between reinjection and the observed seismicity—removing ambiguity in linking wastewater production to seismicity and thus opening the way to mitigation.

A misperception is that increased hydraulic fracturing for shale gas is the culprit for the increase in induced seismicity seen in North America. Rather, it is the reinjected disposal of the large volumes of coproduced brines from conventional hydrocarbon reservoirs that are principally implicated (*8*). Although the much smaller (but appreciable) volumes of fracturing fluid have also contributed to smaller seismic events, the evidence directly linking observed seismicity to active

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hydraulic fracturing is generally ambiguous. However, Bao and Eaton provide compelling evidence directly linking a magnitude-3.9 event in Alberta to hydraulic fracturing of a gas shale. Seismicity initiated several weeks after the initiation of hydraulic fracturing and continued for 4 months after pumping had stopped. Although Bao and Eaton's analysis lacks the geodetic (InSAR) constraint for the case of wastewater disposal (*8*), the role of hydraulic fracturing—and its interaction with large faults that also intersect basement rocks underneath the reservoir—seems clear. Most interesting is that seismic failure occurred on two strands of a fault, but in response to very different triggers.

The first event was triggered when elevated pore fluid pressures from the injected fracking fluids diffused outward to reactivate a tectonically primed strand of a deep fault cutting basement rocks. This strand failed once a sufficient portion was weakened, a mechanism identical to triggering from wastewater injection (*8*). However, the second triggering mechanism had much greater reach from the hydraulic fracture. In this case, failure was driven by elevating the far-field stress beyond the immediate region inflated by the bladelike hydraulic fractures (see the figure inset). This implies two distinct mechanisms for seismicity: (i) a proximal region where pore fluid pressures are elevated and failure is driven by a reduction of the strength of the fault, with the stress state in the local rock mass remaining essentially unchanged, and (ii) an encapsulating aureole, which is as yet unpenetrated by pore pressure diffusion but where increased rock stress drives fault failure while fault strength remains largely unaffected. These two different styles of failure act on similar time scales but are characterized by different length scales.

For now, management strategies for mitigating seismicity associated with wastewater injection have a reasonable basis. Elevated pore pressures contributing to seismicity are reduced if injection rates are curtailed, if injection is distributed over multiple wells across the aquifer, or if injection wells are carefully located away from tectonically primed deep faults. However, solutions are less simple for hydraulic fracturing, in which wells must be located within the hydrocarbon reservoir with no possibility to relocate and the size, reach, fluid-conductivity, and ultimate effectiveness of the fracturing treatment all depend on a high fluid injection rate.

The constrained analysis of wastewater reinjection provided by Shirzaei *et al.* (*8*) helps clarify the debate over causality between injection and induced seismicity, and the observations by Bao and Eaton (*5*) dispel the notion that events resulting from hydraulic fracturing are always small. These studies provide important steps toward answering the key question in the induced seismicity debate: What is the size of the probable maximum event (*9*) based on sound and established scientific principles? Only through such mechanistic understanding can induced seismicity be fully understood and mitigated. ■

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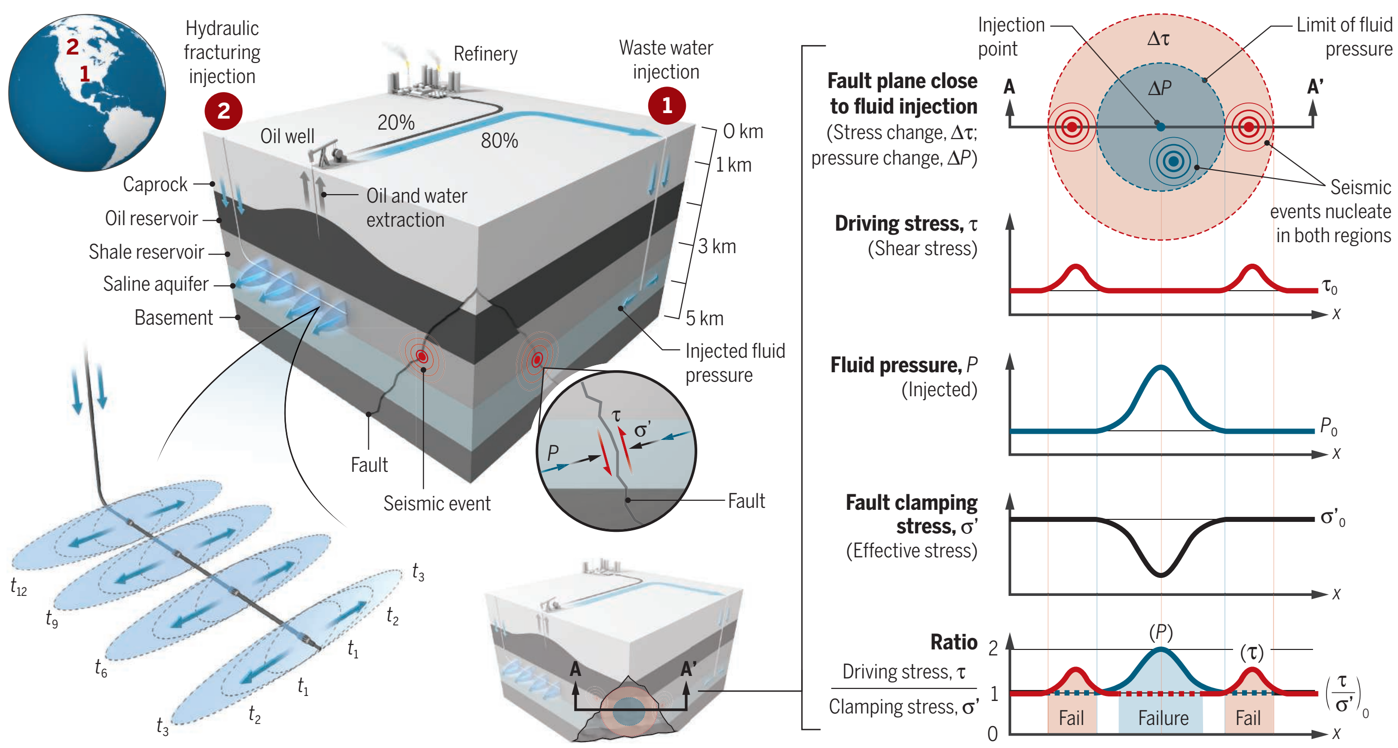
10.1126/science.aal2584

Induced seismicity

A vertical well taps a conventional oil reservoir whereas a horizontal well accesses a shale reservoir for gas. Wastewater reinjection into a saline aquifer (shown in 1) and the injection of fracturing fluid (principally water) into the shale reservoir (shown in 2) have the same impact in elevating fluid pressures and driving the stress state on a deeply penetrating fault to failure. In cross section A-A', injection of fluid near the fault causes slip by contrasting mechanisms in both the near-field and the far-field. The net effect of these two mechanisms is to elevate driving stress above the clamping stresses in these two concentric regions, and to potentially induce seismic slip.



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