Ohio rumblings. Wastewater injected at this site in Youngstown triggered jolting earthquakes that prompted injection-well shutdowns and strong new regulations.

SEISMOLOGY

Learning How to NOT Make Your Own Earthquakes

As fluid injections into Earth's crust trigger quakes across the United States, researchers are scrambling to learn how to avoid making more

First off, fracking for shale gas is not touching off the earthquakes that have been shaking previously calm regions from New Mexico to Texas, Ohio, and Arkansas. But all manner of other energy-related fluid injection—including deep disposal of fracking's wastewater, extraction of methane from coal beds, and creation of geothermal energy reservoirs—is in fact setting off disturbingly strong earthquakes. These quakes of magnitude 4 and 5 are rattling the local populace, shutting down clean energy projects, and prompting a flurry of new regulations.

Researchers have known for decades that deep, high-pressure fluid injection can trigger sizable earthquakes. But after a decades-long lull in triggered quake studies, researchers are playing catch-up with the latest round of temblors. When triggered quakes surprise drillers, "we're often in the position of ambulance chasers without the necessary science done ahead of time," says seismologist William Ellsworth of the U.S. Geological Survey (USGS) in Menlo Park, California.

As researchers link cause and effect in recent cases of triggered seismicity, they are beginning to see a way ahead: learn as you go. Thorough preinjection studies followed by close monitoring of cautiously increasing injection offer to lower, although never eliminate, the risk of triggering intolerable earthquakes.

An injection too deep

"I'm told it feels like a car running into the house," says Stephen Horton, speaking of the magnitude-4 triggered quakes he saw coming a couple of years ago in north-central Arkansas. In the current March/April issue of *Seismological Research Letters*, the University of Memphis seismologist recounts his learn-as-you-go experience with injection-triggered quakes strong enough to seriously shake up the locals.

Quake masters. USGS geophysicists Barry Raleigh (*left*) and Jack Healy are poised to open a valve and pressurize deep rock to turn on earthquakes. They could also turn them off in this 1970s study.

Fracking for natural gas, formally known as hydraulic fracturing, had come to Arkansas around 2009. Not that a seismologist in Memphis would have noticed. Injecting water into gas-bearing shale at high pressures does break the rock to free the gas—that's the point, after all. But the resulting tiny quakes rarely get above magnitude 0 (the logarithmic scale includes negative numbers), never mind to the magnitude-3 quakes that people might feel.

But shale gas drillers need to dispose of the millions of liters of water laden with natural brines and added chemicals that flow back up after a shale gas well has been fracked (*Science*, 25 June 2010, p. 1624). Injecting fracking wastewater into deep rock is a common solution, so starting in April 2009, 1- to 3-kilometer-deep disposal wells were sunk in the vicinity of Guy (population 706) and Greenbrier (population 4706), Arkansas.

That's when Horton and Scott Ausbrooks of the Arkansas Geological Survey took note of a curious cluster of earthquakes near Greenbrier. The Guy-Greenbrier area had had only one quake of magnitude 2.5 or greater in 2007 and two in 2008. But there were 10 in 2009, the first year of deep disposal, and 54 in 2010. The suspicious timing of the quake cluster—which included hundreds of small quakes with one of magnitude 3.0—and its location near the first disposal well got their attention.

Once alerted to the suspicious quakes, Horton and Ausbrooks cast a network of seismometers around two new wells that would start injecting in July and in August 2010. On 1 October of that year, Horton warned the director of the Arkansas Oil and Gas Commission, the state agency that regulates deep injection, to "watch out" for more earthquakes. Ten days later, a magnitude 4.0 struck about a kilometer northeast of the deeper of the two new wells. On 20 November, a magnitude 3.9 struck 2 kilometers farther to the northeast toward Guy. Then, in February 2011, magnitude-4.1 and -4.7 quakes struck to the southwest of the deeper well, toward Greenbrier.

By spring, nearly 1000 recorded quakes had struck the area since the wells had started up. "People were feeling a lot of earthquakes,"

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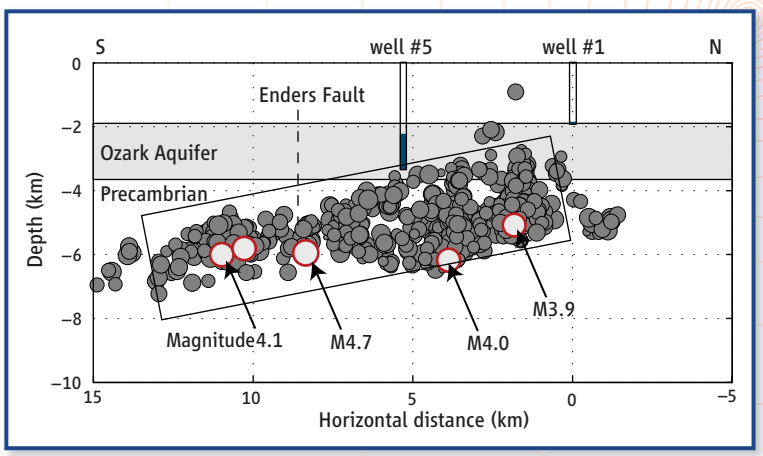
Horton says. By 4 March, the public, the Oil and Gas Commission, and the governor agreed that it was all a bad idea, and the wells were shut down. The quakes tapered away.

"I have no problem convincing scientific audiences these earthquakes were induced" by the deep wastewater disposal, Horton says. Their timing and location were certainly strongly suggestive. The quakes began only after injection began, surged when the rate of injection surged, were limited to the vicinity of the wells, and trailed off after injection was stopped.

But the data from the seismometer network also painted a detailed picture of exactly how the injected wastewater triggered the quakes. It was injected into an aquifer 3 kilometers down, where it increased the pressure of groundwater in the rock's pores and fractures. From there the increased pressure due to injection spread through a previously unknown buried fault into the underlying rock, triggering quakes on the fault as it went.

Those elevated pressures could spread far and wide. Tens of thousands of cubic meters of wastewater were injected each month, month after month; fracking usually involves far smaller volumes pressurized for hours or days. Only in the deeper rock could the added pressure of the injection trigger magnitude 4s. Burdened by far more overlying rock, the deep rock is already carrying stress that will make for larger earthquakes.

The deep rock of the Guy-Greenbrier fault is also innately stronger than the overlying aquifer's sedimentary rock. The stronger rock could therefore store the stress that plate-tectonic forces load onto the North American continent. In this setting, the widespread fluid pressures of injection could pry apart the two sides of the fault just enough to let them suddenly slip by each other and release long-stored tectonic stress as a sizable earthquake.



Bad leak. Wastewater injected into the Ozark aquifer of Arkansas leaked into a deeper unknown fault (roughly outlined by the rectangle in this side view). The heightened water pressure in the fault relieved just enough of the squeeze on the fault to allow earthquakes (gray and orange circles).

A trigger here, a trigger there

North-central Arkansas is not the only place where fiddling with Mother Nature has lately set off earthquakes. On 9 March, the Ohio Department of Natural Resources announced that it had evidence "strongly indicating" that wastewater injection—at least part of it from fracking—had triggered 12 magnitude-2.0-to-4.0 quakes in Youngstown (population 66,982) since March 2011. The indications were strong enough to prompt the state to order the shutdown of four injection wells in the area and issue strong new regulations. And injection of fracking wastewater under the Dallas/Fort Worth International Airport in Texas triggered a sequence of more than 180 earthquakes ranging up to magnitude 3.3 in 2008–2009. The quakes tapered off once the injection was stopped.

Other pursuits of cleaner energy can apparently also trigger earthquakes. Ellsworth and his Menlo Park USGS colleagues will report at next month's annual meeting of the Seismological Society of America that a "remarkable increase" in magnitude-3 and larger earthquakes since 2000 in the central United States is "almost certainly manmade." In addition to the Arkansas cluster, seismic activity surged along the Colorado–New Mexico border beginning in 2001. That's where drillers were injecting water to extract methane from still-buried coal beds. In central and southern Oklahoma, seismicity abruptly increased in 2009 by a factor of 20 over the rate of the previous half-century, exclusive of November's magnitude 5.6 and its aftershocks. Exactly what is causing the Oklahoma surge is still unclear, but "we're suspicious industrial activities are at the heart of what's going on" all across the central United States, Ellsworth says.

Drillers are running short of ideal waste injection sites, says geophysicist Mark Zoback of Stanford University in Palo Alto, California. There are already 144,000 wastewater injection wells in the country, he notes, but almost none trigger quakes. That's probably because they were drilled into weak, porous rock well suited to accommodating injected fluids. But some areas new to drilling are far from suitable rock formations. Deep, brittle, low-permeability rock "doesn't have a lot of capacity for taking any of these fluids," says geophysicist Barry Raleigh, who ran the Rangely, Colorado, earthquake-control experiment in the 1970s (see photo, left). "As a storage medium, they're pretty crappy."

Red light, green light

Wastewater injection "is not a mysterious process," Zoback says. "These are manageable problems. We simply have to be more careful." In his article in the April issue of *Earth*, Zoback lays out a learn-as-you-go approach to locating injection operations similar to one that geophysical modeler Jonny Rutqvist of Lawrence Berkeley National Laboratory suggested in a January *Geotechnical and Geological Engineering* article. Learn-as-you-go would likely also apply to fluid injections to create geothermal energy reservoirs (injections beneath Basel, Switzerland, touched off a project-ending magnitude-3.4 quake in 2006) or to keep the greenhouse gas carbon dioxide out of the atmosphere.

Zoback's first recommendation is to look before you leap. He believes that the seismic imaging techniques used in oil and gas exploration should easily find buried faults capable of producing damaging quakes—those above, say, magnitude 6.0.

When injection begins—and it should begin cautiously, Zoback says—seismometers should be monitoring the area. At a minimum, their data could paint a subsurface picture in real time, as in Arkansas, that could reveal smaller faults capable of magnitude 4s and 5s. But seismic data and well observations could also be fed into models of crustal rock behavior that could, with considerable uncertainties, project the potential for sizable earthquakes. If actual or projected quakes emerged, injection could be throttled back or even stopped, Zoback says. (Stopping injection has stopped significant earthquakes within days to a year.)

The new regulations in Ohio and Arkansas at least move in the direction of such a learn-as-you-go approach. Studies by the U.S. Environmental Protection Agency and by the National Research Council on the injection triggering of quakes are due out in the coming months. **–RICHARD A. KERR**