



Shaken by injection. Deep fluid injection induced an alarming quake beneath Youngstown, Ohio.

SEISMOLOGY

Some Earthquakes Warn That They Are About to Strike

The bad news that injecting wastewater deep into the crust can set off earthquakes has now been leavened by a bit of good news. In the past few years, the frequency of moderate-sized earthquakes has surged in parts of the United States where wastewater from “fracking” for gas and oil is pumped into the deep earth for disposal. Now, seismologists have found that some of the largest quakes induced by deep injection are preceded by a warning sign: a distinctive swarm of smaller tremors.

The practical value of the discovery is limited. It applies to earthquakes linked to fluid injection, not as yet to large natural quakes along faults such as the San Andreas. Not all injection-related quakes ever telegraph their moves. And the warning depends on the chance occurrence of large, distant quakes that tickle local faults into low-level activity shortly before injection induces a larger quake. But to researchers who have searched in vain for any kind of earthquake warning sign, the finding is a milestone.

“We’ve been looking for this for years,” says seismologist Emily Brodsky of the University of California, Santa Cruz. “This is one of the holy grails—a way to probe the state of stress of the crust. This shows you can do it.”

Seismologists have long recognized that deep injection can induce earthquakes. The injection increases the fluid pressure along a fault that is already under stress, which can counteract the forces squeezing the fault together and make it more likely to rupture.

Sure enough, in the past few years, quakes of magnitude 4 and 5—alarming but barely destructive—began to shake sites of deep injection in the eastern two-thirds of the United States (*Science*, 23 March 2012, p. 1436). With public concern soaring, seismologist Nicholas van der Elst of Columbia University’s Lamont-Doherty Earth Observatory in Palisades, New York, and colleagues decided to search the seismic record near places where deep injection has been physically linked to sizable quakes for any premonitory signs.

Aiding their search were the 400 traveling seismic stations of the USArray (*Science*, 14 June, p. 1283), which boosted the available data by supplementing the fixed seismic stations across the United States. Van der Elst and colleagues analyzed the data using a technique that matches the seismograph squiggles of quakes that strike the same spot, so they could detect patterns in earthquake times and locations.

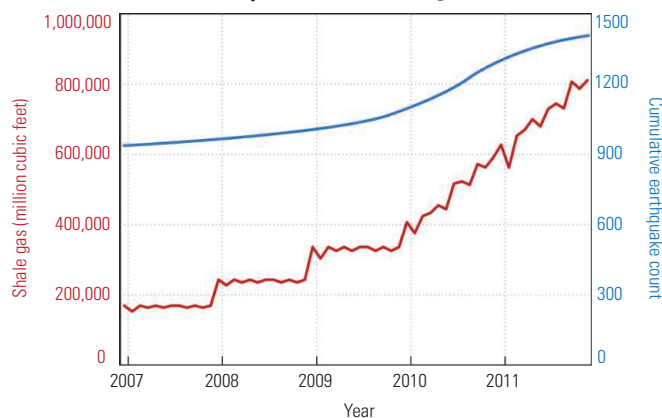
As they report this week in *Science* (p. 164), the warning sign of an impending human-induced earth-

quake turned out to be swarms of smaller quakes set off by passing seismic waves from large, distant quakes. During the 10 days after the March 2011 great Tohoku-oki earthquake off Japan, almost a score of quakes ranging up to magnitude 3.8 struck near Snyder, Texas, where an injection-induced magnitude 4.5 later struck on 11 September of that year. A great quake before Tohoku-oki and one after the induced Snyder quake triggered no swarms near Snyder. A similar seismic pattern related to distant triggering quakes appeared around three large (magnitude 5.0 and larger) human-induced quakes near Prague, Oklahoma, in November 2011. The pattern, weaker but still identifiable, also was found around the human-induced seismic swarm at Trinidad, Colorado, in August 2011 that ranged up to magnitude 5.3.

Van der Elst and colleagues analyzed records from the areas of three other injection-induced quake swarms, but they found no precursory triggering by large distant earthquakes. Because all three swarms struck not long after injection began, the researchers suspect there simply happened to be no distant quakes large enough to trigger a warning swarm during the short time when the sites were vulnerable.

“It might not happen every time,” says van der Elst of the remotely triggered warning quakes, but “where it does happen indicates you should be careful.” Seismologist William Ellsworth of the U.S. Geological Survey (USGS) in Menlo Park, California, agrees. It would be “wise to be alert to the

Earthquakes and Fracking Wastes



Quakes followed fracking. Natural gas production (red) from fracking shale soared as central U.S. seismic activity accelerated (blue, smoothed approximation).

possibility of [remote] triggering,” he says. “That’s a sign that it might be prudent to back off on injection pressures and rates.”

Researchers say that it makes sense that a passing seismic wave would elicit quakes from a fault already weakened by fluid injection. In waterlogged crust riddled with faults that are on the verge of failing—such as southern California’s Salton Sea geothermal region—passing seismic waves ever so slightly pump up fluid pressure and trigger small quakes just as deep injection is thought to do.

Remote triggering won’t likely be incorporated into deep injection regulations anytime soon—the science is hardly mature—but drillers doing deep injection will no doubt be taking note. They already know a surge in seismicity at the start of injection is a bad sign. And the hubbub over human-induced quakes has accelerated efforts to treat fracking wastes for surface disposal or to reuse them to cut down on the volume requiring deep disposal.

Remote triggering could also be important for anticipating quakes that pop off on

their own without human help. But it won’t be *the* holy grail of earthquake prediction, researchers say. Remote triggering, notes seismologist David Hill of USGS in Menlo Park, requires not only a well-timed distant quake of magnitude 7 or above, but also free-flowing fluids in and around the fault of interest. The San Andreas fault, for one, seems to lack free-flowing fluids, perhaps because of the unfavorable orientation of cracks around that type of fault. In any case, no remote triggering has ever been seen on the San Andreas.

—RICHARD A. KERR

EVOLUTION

Field Test Shows Selection Works in Mysterious Ways

SNOWBIRD, UTAH—From a distance, Rowan Barrett, a slight man with a thick black beard, doesn’t really stand out in the crowd. But his peers think that he does. For the past 2 years, Barrett has swept the main awards for young evolutionary biologists, capping off his run last month at the Evolution 2013 meeting with the Dobzhansky Prize from the Society for the Study of Evolution. His claim to fame: daring to do experimental evolution on a grand scale to examine how selection shapes an organism’s whole genome.

“He’s proven that he’s not afraid to dive in and test hypotheses in a natural setting in situations where it was previously thought that it would be too difficult to test,” says Robin Hopkins, an evolutionary biologist at the University of Texas, Austin. “He has incredible persistence.”

Barrett works in the Sand Hills of Nebraska, where mice living on the light-colored dunes are lighter in color than those in the surrounding prairie. Researchers have long assumed that the dune mice lightened up to become less visible to airborne predators such as owls, and studies have pinned down changes in a pigment-related gene called *Agouti* in these mice (*Science* 28 August 2009, p. 1095; 15 March, p. 1312).

That tidy tale left Barrett dissatisfied. “This has been one of the longest-standing adaptive stories in evolutionary biology, but the hypothesis that cryptic coloration is adaptive has never been directly tested in deer mice under natural conditions,” he says.

It has now. Barrett told the audience at the evolution meeting that his preliminary results suggest color does protect the dune mice—but that other genes also help the mice thrive. The results show that “there are other things that played a role in adaptation,” says David



Tracking evolution. Using big field enclosures, researchers are monitoring the evolution of deer mice.

Reznick, an evolutionary biologist from the University of California, Riverside.

Barrett began the work in 2010, as a postdoc with Harvard University’s Hopi Hoekstra. He and his colleagues trapped hundreds of Nebraska deer mice living on light and dark ground, characterizing their coats, sampling their DNA, and marking them for follow-up studies. They then released sets of about 100 mice—half from each environment—into six 50-meter by 50-meter enclosures in the Sand Hills and on dark soil nearby. Steel fences 1.5 meters tall, extending 60 centimeters underground to prevent burrowing, kept the mice from escaping, but did not protect them from airborne predators. Every few months for 2 years, the researchers trapped all the mice in each enclosure, tracking which were still alive and monitoring shifts in the frequency of different versions of the rodent’s genes.

Not surprisingly, dark mice did better on the dark soil, and light mice did better on the light sand. On a genetic level, Barrett’s anal-

ysis confirmed the importance of the *Agouti* gene—multiple differences in its sequence were either favored or selected against in the various enclosures. “Selection is on a fairly broad region of the *Agouti* gene,” says Dolph Schluter, an evolutionary biologist at the University of British Columbia, Vancouver. “It’s not just the case of one mutation being favored.”

But many genes not related to pigment also changed over the course of the experiment. The analysis revealed “a potentially large number of genetic regions responding to selection,” Barrett reported. He doesn’t know what traits those changes affect, but he’s investigating each one—and suspects some have nothing to do with surviving predation. They might make a mouse healthier overall, or better able to find food, for example.

“A lot of what we know about selection is very crude,” Schluter says. “When we start to do experiments we are surprised to find stuff happening that we didn’t anticipate.”

—ELIZABETH PENNISI

CREDIT: ROWAN BARRETT