ENVIRONMENT

Can We Stop The Surge Of Man-Made Earthquakes?

There's a whole lot more shaking going on in the Midwest lately—and humans are causing it.

December 22, 2015

Earthquakes East Of the Rockies, 1973-2014.

In a recent study, published in *Science*, geophysicists analyzed earthquakes east of the Rockies and found a strong link to injection sites. Those colored in red were near active wells. Those in gray were not. *Katie Peek / Popular Science / Source: M. Weingarten et al., Science, 19 June 2015*

Mark Crismon and I were sitting outside his Oklahoma house, looking at the day lilies that lined his pond, when our conversation was interrupted by a distant boom. “Did you feel that?” Crismon asked.

“Just be quiet. Sit still.” He’s a lanky 76-year-old, retired from an electronics career, with gray hair combed straight back from his ruddy face. The booms continued, once or twice per minute; I felt them under my skin. “That’s a small earthquake,” he said, seconds before the sound recurred. “There it was again. We’ll go and look on the seismometer—I’ll show you what it looks like.”

We walked into his garage. It was July and approaching 100 degrees in the countryside north of Stillwater. The building was filled with freezers where Crismon and his wife store the food they grow, catch, shoot, and smoke. Deer and coyote tails covered corrugated-tin walls. On a desk in the corner, beside a hand-labeled bottle of peach brandy, sat a Dell laptop connected by a cable to a buried seismometer. Oklahoma State University scientists had given Crismon the seismometer in 2014, as part of a project to monitor the state’s current rash of earthquakes.

He took a drag from his cigarette, then turned his attention to three parallel bars scrolling across the screen: blue on the bottom, red in the middle, green on top. They were mostly straight but had become jagged for the several minutes we had felt the tremors. “How’d you like to put up with that day and night?” he asked.

Earthquakes in Oklahoma

Mark Crismon monitors earthquake activity caused by injection wells at his home in Oklahoma, as part of a seismic network set up by scientists. *Sebastian Meyer*

Crismon sits at this desk, on and off, for 14 hours a day. He arrives at six in the morning and takes pictures of the spikes with a digital camera to document what he calls a growing menace (even though

the data gets recorded regardless). There's plenty to photograph: Oklahoma, which historically has had few earthquakes of magnitude 3.0 or higher, started rumbling regularly in 2009. The Oklahoma Geological Survey recorded 35 such quakes in 2012, 109 in 2013, and 584 in 2014. (The prior annual average was fewer than two.) By late October, the 2015 figure had already exceeded 700.

Scientists have figured out the reason: the oil-and-gas industry's practice of injecting wastewater deep underground.

The granite basement that underlies the continent, a mile below Oklahoma’s wheat and alfalfa fields, is full of faults. Usually, natural stresses clamp the rocks and keep them from moving—like “a vise that’s slammed on the east and west side, and someone’s turning the screw,” says Todd Halihan, a hydrogeophysicist at Oklahoma State University. Inject fluid deep enough, he says, and it travels into the fractures in the granite, in effect lubricating the rock and causing faults to slip.

Halihan compares this to tabletop air hockey. "When it's off, the puck doesn't move particularly well," he says. "Turn on the air, and it's like you're injecting. That puck moves *real* well."

Sometimes these quakes arrive as jolts like those Crismon and I felt outside his house. Sometimes they topple buildings and claim lives.

It's not only in Oklahoma where we're giving the proverbial puck more room to slide. Our species, unintentionally, keeps finding new ways to unleash earthquakes. We have rattled the ground by impounding reservoirs, excavating mines, testing nuclear weapons, tapping geothermal power, and

pushing carbon dioxide underground to slow global warming.

Sometimes these quakes arrive as jolts like those Crismon and I felt outside his house. Sometimes they topple buildings and claim lives. Whether they hit the Midwest, California, Switzerland, India, or China, some of those who feel the shocks are asking: Can we control the tremors, or are damaging quakes an inevitable feature of the future?

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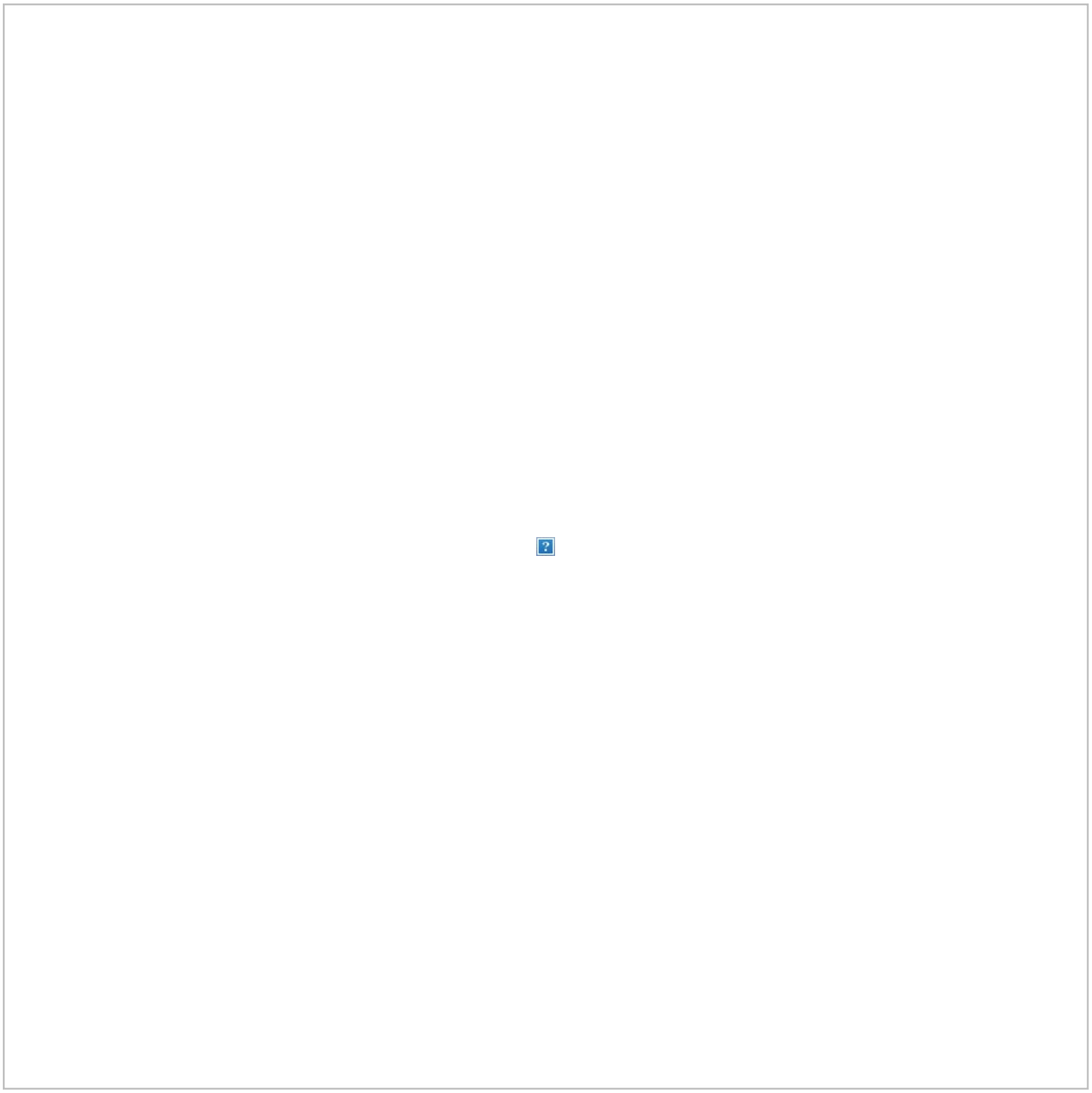
We first recognized the problem of man-made earthquakes around the turn of the 20th century, as they began hitting the regions around South Africa's gold mines and Europe's coal mines. The release of gravitational energy, when the rock above the mines sagged, triggered them.

It took until the 1930s for Americans to notice man-made quakes beneath our own soil. When engineers created Lake Mead behind the Hoover Dam, the sudden addition of 12 billion tons of water apparently set off hundreds of small tremors along the Arizona-Nevada border.

“This was an ‘aha moment,’ an important benchmark in the science,” says Bill Ellsworth, an emeritus seismologist with the U.S. Geological Survey and geophysics professor at Stanford University. Since then, reservoirs have been linked to devastating quakes around the world: definitively to a magnitude-6.3 quake that killed 200 people in 1967 near India’s Koyna Dam, and more speculatively to the 2008 Sichuan quake, a magnitude-7.9 colossus that flattened schools and hospitals in China, and left more than 80,000 people dead or missing. The Sichuan quake was triggered less than 6 miles from the Zipingpu Dam reservoir, says natural-hazards researcher Christian Klose, who has linked water levels there to tremor frequency.

The most ominous precursor to Oklahoma came in the 1960s, when a series of earthquakes walloped the normally quiet Denver area. During two particularly lively days in 1962, the shocks broke windows, cracked plaster, and left electrical outlets hanging by wires. “Children cried with fright,” read a federal field report from Dupont, a town just north of the city.



Earthquakes in Oklahoma

Oil-and-gas operations produce wastewater made up largely of brine. Injection wells in the U.S. pump 2 billion gallons of it a day underground. *Sebastian Meyer*

Scientists traced this seismic uptick to the Rocky Mountain Arsenal, an Army facility that manufactured chemical weapons and rocket fuel. Weeks before the trembling began, the arsenal had

started injecting wastewater 2 miles down into the crystalline basement rock. After the injections stopped, in 1966, it took a year for the shaking to cease: A magnitude-5.3 quake knocked bricks from chimneys in 1967 and caused more than $1 million in damage.

A geologist named David Evans found an association between the amount of fluid injected at the arsenal and the number of earthquakes, and suggested cause and effect. (To demonstrate how lubricated rocks slip, Evans reportedly would perform the "Coors experiment": He perforated the bottom of a beer can, and then showed how the seeping liquid eased its slide down an incline.) The Army disputed Evans' hypothesis, but he was vindicated by USGS researchers, who triggered seismicity soon after by methodically injecting fluid into Colorado's Rangely oil field.

Since then, scientists have grown more sophisticated about documenting changes in earthquake activity. About 200 miles south of Rangely, in Colorado's Paradox Valley, the U.S. Bureau of Reclamation has been injecting briny groundwater into a deep limestone formation in order to keep it from contaminating a river. "Somebody had the foresight to say, 'Let's see what kind of seismicity's out there before we start injecting,'" says bureau geophysicist Lisa Block. Six years of baseline data showed almost no natural activity. By contrast, the agency has recorded 6,200 quakes, most of them small, since underground disposal began in 1991.

By the time Oklahoma starting ramping up its own wastewater injection—now more than a billion barrels a year—the notion that humans can induce earthquakes by putting fluid underground was already familiar. Still, Sooner State residents were caught off-guard when that geologic principle hit home.

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The Surge in Shaking

A decade ago, this part of North America experienced just 14 tremors a year. In 2014, 650 quakes hit the area, most of them clustered around wastewater injection wells.

Both maps show tremors stronger than magnitude 3.0. Color represents strength; dots mark centers. The map omits a few quakes along the west of New Mexico and Colorado, to avoid earthquake-prone mountain regions. Source: U.S. Geological Survey National Earthquake Information Center *Data visualization by Pitch Interactive*

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Todd Halihan was standing in the hallway of his Stillwater home one night in November 2011 when

he noticed glasses starting to rattle. As the building shook, the hydrogeophysicist flashed on his sleeping 6-year-old. "Should I get my kid out of bed and run out of the house?" he recalls thinking. "Should I get him under a table?"

Halihan was feeling the effects of a magnitude-5.7 quake—Oklahoma's largest, it turns out. Its center was near Prague (rhymes with "vague"), almost 50 miles away, where it buckled a highway and destroyed 14 homes. In one living room, rock from a fireplace and chimney struck a woman as she watched TV. The earthquake also toppled a historic turret at St. Gregory's University in nearby Shawnee. A team from the University of Oklahoma, Columbia University, and USGS determined the source: a fault rupture that began about 650 feet from active injection wells.

"That's when a lot more people started paying attention," says Austin Holland, Oklahoma's state seismologist until this past summer.

The idea that the oil-and-gas industry could be producing these quakes was a touchy subject, both for companies and for the administration of Gov. Mary Fallin. One study shows the industry has created one-fourth of Oklahoma's new jobs since 2010. Emails obtained by the EnergyWire news service paint a picture of a government that, in the words of Fallin chief of staff Denise Northrup, tried to "make this go away." Shortly after the Prague earthquake, Fallin aides contacted Devon Energy, an oil-and-gas producer, and obtained talking points to use with constituents. Among them: "There is no current evidence that oil-and-gas operations had anything to do with the recent large earthquakes in Oklahoma." When Fallin addressed a National Governors Association forum on shale-energy development in 2013, a reference to underground injection wells was deleted from her speech. "We had other issues we wanted to highlight," says Alex Weintz, Fallin's communications director until this past November.

The problem doesn't stop at Oklahoma's borders; man-made earthquakes have hit other midcontinent states too.

Weintz says Fallin's personal views were always more nuanced than Devon Energy's talking points, even if those points were used by her staff. Her own reticence to blame disposal wells, he says, reflected the state of the research when she took office in 2011. "It was only the beginning of a spike in seismic activity," he says. "Since then, the science has evolved."

Even the Oklahoma Geological Survey, a university-affiliated state agency, was slow to acknowledge the disposal-well connection. In a 2013 statement, it noted that the Prague earthquake appeared to be the result of "natural causes." Holland, who worked for the survey, says, "Oil-and-gas is a very important industry, and so . . . some of the public statements saw a lot of wordsmithing."

As scientists dug into data, a consensus emerged that fluid injection was indeed behind the spike in

earthquake activity. Even Fallin has come around. “We all know now there is a direct correlation between the increase of earthquakes that we’ve seen in Oklahoma and the disposal wells,” she said at an August meeting of her administration’s Coordinating Council on Seismic Activity.

In fact, new research shows earthquakes now pose a risk to the oil- and-gas industry itself. The largest crude-oil storage facility in the world sits in Cushing, Oklahoma, right above a fault recently activated by injection. Continued injection could produce a magnitude-5.7 earthquake, large enough to rupture oil tanks and pipelines.

The problem doesn’t stop at Oklahoma’s borders; man-made earthquakes have hit other midcontinent states too. On New Year’s Eve 2011, a magnitude-4.0 tremor in Youngstown, Ohio, shook buildings and led to the shutdown of a disposal well that was deemed the likely culprit. Waste injection has also been linked to quakes in Arkansas, Colorado, Kansas, New Mexico, and Texas.

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If the same quakes had happened overseas, they might have caused far more damage. “The technologies that have been pioneered primarily in the U.S.—to unlock gas from tight shale and to produce oil from unconventional reservoirs—have the potential to be applied around the world,” says Ellsworth, the USGS seismologist. “Many countries will find it irresistible to produce their own resources. Unfortunately, in many of these countries, the building standards are not what they are in the United States, and the potential for severe damage and loss of life is really high.”

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As we keep using the earth as a vault to stash our waste—and as a tappable resource—we're creating a global-energy system that will likely increase the risk of small and potentially large earthquakes. Engineers will need to weigh every resource, looking at how much power it provides, how green it is, and what type of seismic risk it poses.

In some cases, the technologies we’ve engineered to ease our impact on the environment have proved likely to shake the ground. In a pilot project in Decatur, Illinois, carbon dioxide captured from an ethanol plant is being injected, in liquidlike form, almost 7,000 feet down into a sandstone formation. The goal is to slow climate change by keeping the greenhouse gas out of the atmosphere (a tactic also advanced by proponents of “clean coal”).

So far, the injections have caused only the smallest of tremors, too faint to be felt. But Stanford University geophysicist Mark Zoback and hydrogeologist Steven Gorelick have argued that for underground carbon storage to benefit the climate, it must happen at a “massive scale”—one that will likely trigger more seismicity, and therefore potentially defeat its own purpose by discharging the

carbon into the atmosphere. “Even small to moderate earthquakes threaten the seal integrity of a CO2 repository,” they wrote in a 2012 journal article. For that reason, they concluded, carbon injection will be “an extremely expensive and risky strategy” to reduce greenhouse gases.

Ole Kaven—a USGS geophysicist involved in the Illinois project—says that if researchers can map faults, fractures, and fluid pathways using sophisticated instruments, they can reduce the hazard, though not eliminate it entirely. “If one factors in the cost of greenhouse-gas emissions, and what effect CO2 sequestration can have on reducing some of the long-term effects, this conversation changes,” he says. “Some of these risks might be tolerated.”

Earthquakes in Oklahoma

Hydrogeophysicist Todd Halihan says it might not take much pressure to increase seismicity—as little as 15 pounds per square inch. “Half of a car tire,” he says. *Sebastian Meyer*

That’s a critical point: A technology might produce earthquakes, but what harm might come from not using it? Take geothermal production, a reliable and underused source of electricity that causes little

environmental damage. “If we could tap all the heat in the earth, we wouldn’t need anything else,” says Ernest Majer, a geophysicist affiliated with both the Lawrence Berkeley National Laboratory and Sandia National Laboratories.

That was no comfort in Basel, Switzerland, where in December 2006 operators of the Deep Heat Mining project began injecting cold water into the naturally hot granite below the city. The following week, a magnitude-3.4 shock rattled windows and cracked plaster. Injection was halted. A government study projected a 15 percent chance of a man-made earthquake causing more than $500 million in damage if production resumed. In 2009 the project was scrapped entirely.

Geothermal production continues in rural areas—most notably at the Geysers, north of California’s Bay Area, where locals have routinely endured minor quake damage. “Sometimes it feels like a big truck just bumped into the house,” says Jeff Gospe, who sits on a seismic-monitoring advisory committee there. Neighbors have reported cracked windows and a retaining wall that crushed a van.

Majer believes that the hazard posed by geothermal fields is minor compared with their potential to produce clean energy. (He says the Geysers alone could power all of San Francisco.) “There’s no such thing as zero risk,” Majer says. “Driving to the grocery store is a risk. Everybody risks when they get out of bed in the morning.” Compare that, he says, with the cost of carbon emissions: “If you start looking at the health impacts, the climate impacts—all the nasty things coming out of the fossil-fuel economy—well, maybe we better do something else. Induced seismicity associated with putting carbon into the ground, associated with geothermal: Those are minor, minor things compared with all these other risks facing us.”

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Assuming we're not going to shut down energy production, scientists now face a more complex question: whether it's possible to minimize the hazard.

After the experiments in Colorado’s Rangely oil field in the 1960s and ’70s, which showed that we could control induced seismicity by varying the pressure of injected fluid, scientists were bursting with hope. Not only might they reduce damage from man-made quakes, the thinking went, but maybe they could control natural ones. Rather than waiting for the next bridge-toppler to hit California, USGS scientists suggested drilling wells along the San Andreas Fault, injecting water, and releasing the accumulated stress in a series of small, harmless quakes.

The idea never got traction. Not only would it take thousands of mini quakes to offset a major one, but it is also too risky. More than a century has passed since San Francisco’s deadly 1906 quake, which means the city is sitting on highly stressed rock. Inject water underground, says Oklahoma’s Halihan, and “you might not release 100,000 small ones. You might release a big one.” Even if the experiment did work locally, he says, “you might set off the next segment of the fault. It’s 3D and it’s complicated: ‘Hey, we didn’t cause an earthquake in San Francisco.’ ‘Well, you just knocked down LA.’ ‘Sorry.’ ”

Today, nobody's talking about setting off microtremors in Oklahoma in order to avoid the next Prague earthquake. But scientists are talking about more-modest ways to manage seismicity.

"The toolbox is growing," says Austin Holland, who now works for USGS in New Mexico. It includes avoiding known faults, scaling back the volume and rate of fluid injected into the rock, injecting at a shallower depth, improving monitoring, and preparing to abandon wells altogether if seismicity can't be stopped. This past year, the Oklahoma Corporation Commission—which regulates the industry—ordered volume reductions for some wells, as well as "plug backs" to limit how deep some wastewater is injected. The state's "traffic light" system, instituted in 2013, allows regulators to scale back or halt drilling in response to seismic activity.

Earthquakes in Oklahoma

A truck carrying wastewater dumps it into a storage facility in Oklahoma before it is re-injected into the ground. *Sebastian Meyer*

Still, eight magnitude-3 and -4 quakes struck northern Oklahoma during a 24-hour period as this story went to press. There's a lot we haven't yet learned about what happens underground—and that knowledge gap stymies us from managing the earthquakes we do create.

“Probably the greatest unknowns are the properties and processes deep within the earth, things that are very difficult to measure directly,” Holland says. “How is pressure being communicated? Do faults act as seals or as conduits? What are the actual stress states deep within the earth? That’s where science has to spend a significant amount of effort and resources.”

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Back in Stillwater, Todd Halihan understands both sides. He wants his students to find work in the energy industry when they graduate. But he also doesn't want to have to dive for his son the next time an earthquake shakes his house.

“We’re going to make some decisions, and none of them are going to be super-simple or super-pleasant,” he says. Ideally, that means talking levelheadedly about both the value of oil-and-gas production and the threat of earthquakes—how to balance those competing concerns and how much uncertainty we’re willing to tolerate.

It’s not easy to talk, though, when the ground is rattling. Each side retreats into a corner. Some industry and political leaders refuse to acknowledge the emerging science. Some quake-zone residents, feeling ignored and outgunned, pull out the only weapon they have: their rhetoric. The conversations grow polarized rather than solution-oriented.

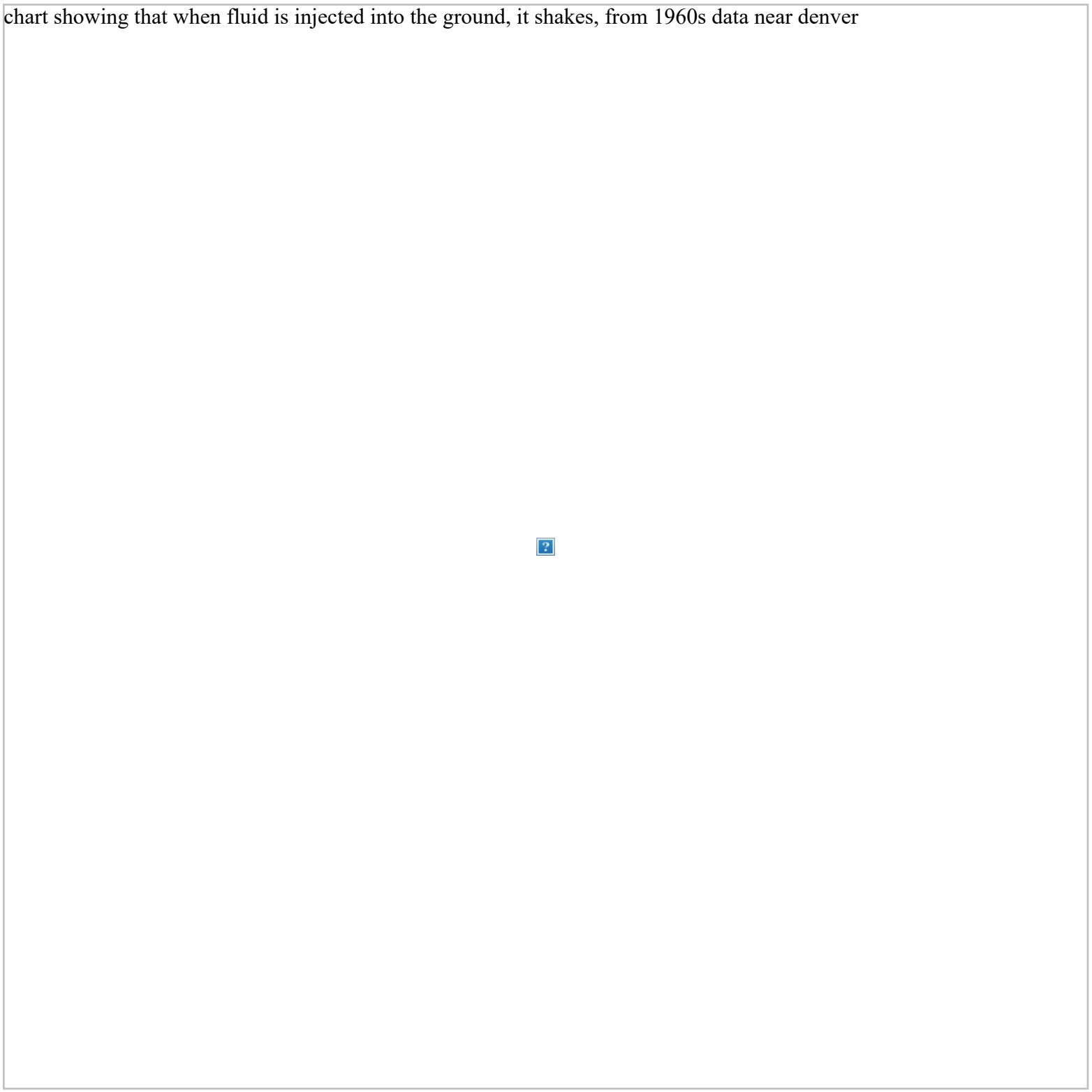
It’s not easy to talk when the ground is rattling. Each side retreats into a corner…The conversations grow polarized.

Technology, Halihan says, often carries harm. “The Titanic’s a nice example,” he says. “We were developing big ships, and we sank them. Developed airplanes; we crashed them.” Addressing unintended consequences doesn’t necessarily mean scrapping innovations. Nor does it mean pretending the consequences don’t exist.

With seismicity, as with addiction, the first step is admitting we have a problem that’s not fully within our control. “The government, as well as these companies, should be upfront,” says Leonardo Seeber, an earthquake geologist at Columbia University’s Lamont-Doherty Earth Observatory. “You want to drive your car. It takes gasoline. To produce that, you have to make wells. You have to pump in here and pump out there. And when you are doing that,” he says, “you are changing the stress in the subsurface. Sometimes there could be earthquakes that we can’t predict. There could be consequences. But we’re all in it together.”

This article was originally published in the January/February 2016 issue of Popular Science, *under the title "Earthquake Nation"*

The Case for Human-Caused Earthquakes, in Charts



Do injection wells really cause earthquakes?

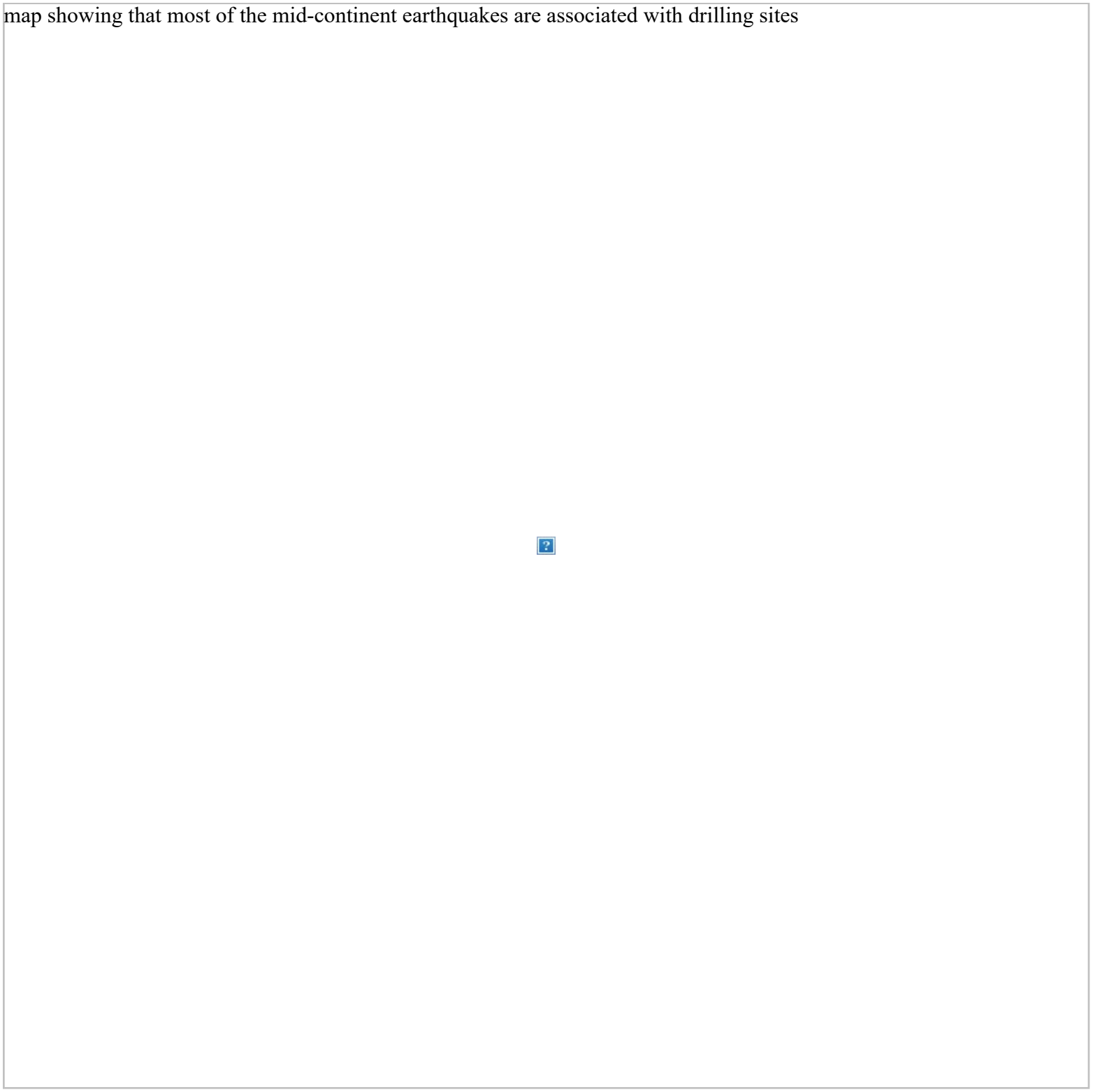
Yes. In the early 1960s, an area near Denver experienced a cluster of 710 earthquakes. The tremors started a month after the Rocky Mountain Arsenal installed an injection well to dispose of waste from chemical-weapons manufacturing. Before 1960, the most recent earthquake in the region had been in 1882. Careful statistical analysis confirmed a trend obvious to even a casual observer: Large volumes of liquid, shot deep into the earth, can cause the ground to shake. *Katie Peek / Popular Science / Source: David M. Evans, The Mountain Geologist V.3, 1966*

bar chart showing the spike in recent quakes and that the spike is largely due quakes near injection wells

Are the recent quakes throughout the U.S. also caused by injection?

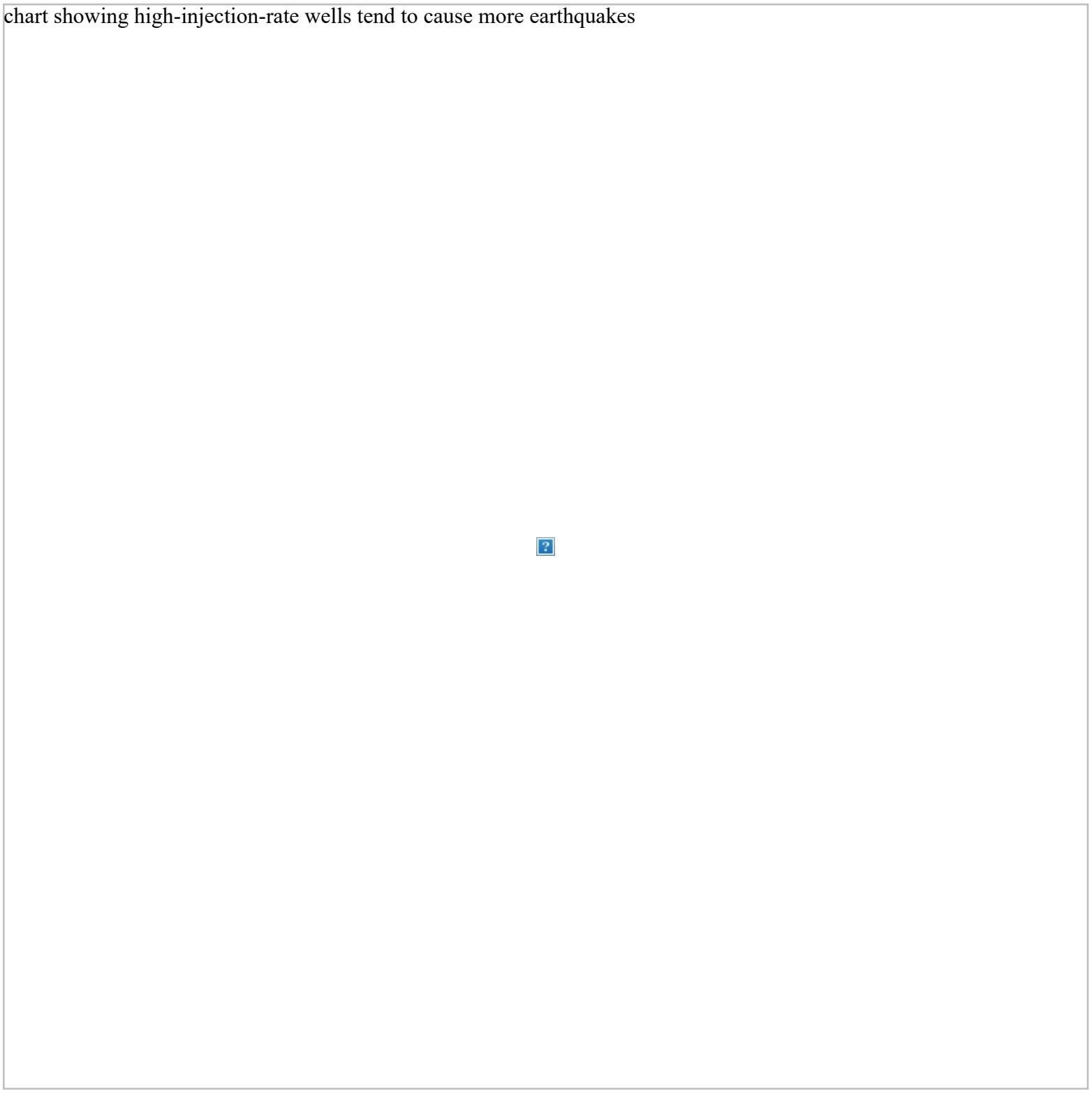
Almost certainly. In a recent study, published in *Science*, geophysicists analyzed earthquakes east of the Rockies and found a strong link to injection sites. Since 2011, 87 percent of tremors stronger than magnitude 3.0 have occurred within 15 miles of an active well. *Katie Peek / Popular Science / Source: M. Weingarten et al., Science, 19 June 2015*

map showing that most of the mid-continent earthquakes are associated with drilling sites



…and it’s not just in Oklahoma

Earthquakes across the eastern U.S. are associated with injection wells. *Katie Peek / Popular Science / Source: M. Weingarten et al., Science, 19 June 2015*



Can oil and gas companies prevent future earthquakes?

Probably. The authors of the *Science* study analyzed more than 7,000 earthquakes and nearly 20,000 wells to identify the practices most likely to be responsible. They found high injection rate was the biggest culprit, at least for saltwater wells. (Such wells inject brine into fresh ground, as opposed to enhanced oil recovery wells, which inject it into oil or gas fields in order to extract fuel.) Injection rate mattered more than well depth or total fluid volume. It's a logical conclusion: Injecting fluid rapidly gives it less time to diffuse, which may raise the pressure that pushes rocks apart at a fault line. But many high injection rate wells operate in states such as Michigan without creating earthquakes, so the structure of the ground is a factor too. *Katie Peek / Popular Science / Source: M. Weingarten et al., Science, 19 June 2015*

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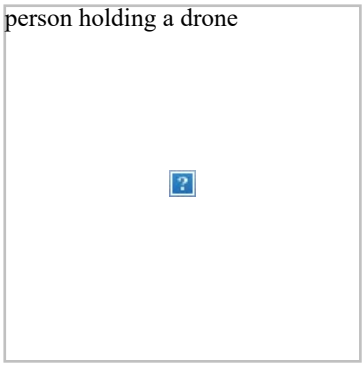

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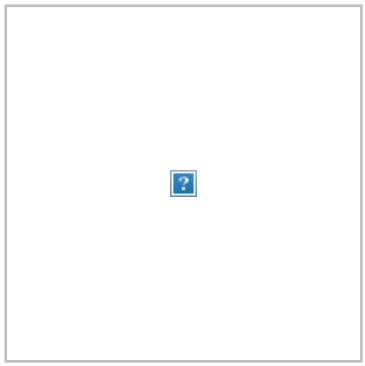

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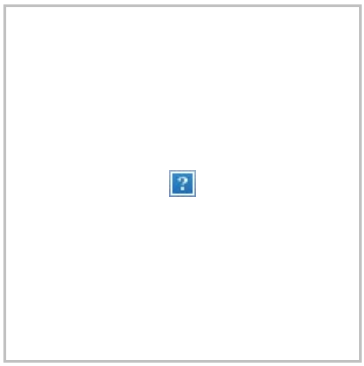

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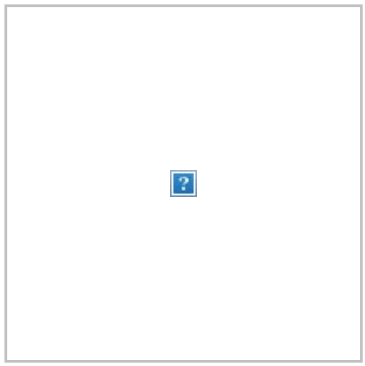

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