parks, Oklahoma, isn’t a place where you would expect a big earthquake. It’s prairie country, smack-dab in the middle of the North American continent, far from the grinding tectonics that keep people in places like California, Japan or Indonesia on edge. Yes, the crust occasionally trembles as ancient rocks adjust to distant stresses, but rarely enough for anyone but a seismologist to notice.

But on 5 November 2011 two substantial earthquakes shook the area. The largest, at magnitude 5.6, was big enough to injure two people, destroy 14 homes, damage many others, and be felt across 17 states. It was the biggest earthquake in Oklahoma’s history, and one of five magnitude 4.7 or larger quakes to strike the US heartland in 2011 and 2012.

Other than being unexpected, one of the main things these temblors have in common is that many, if not all, appear to have been induced by human activities, specifically oil and gas extraction.

"It’s the hottest topic in seismology," says Ivan Wong, vice president and principal seismologist at URS, an Oakland, California, consulting firm. "And definitely an issue that the oil and gas industry needs to address."

It’s not just a problem in America. Oil-and-gas-related quakes have also shaken France, Germany, the Middle East, and the Netherlands, says Christian Klose, a research scientist at Think Geohazards, a New York-based consulting company.

The implications are huge for the burgeoning natural gas industry and its increasing reliance on hydraulic fracturing (commonly called fracting). The relatively new drilling method injects high-pressure fluids deep into the Earth to loosen oil and gas deposits. It’s a controversial approach: since the late 2000s, media attention has focused on potential groundwater contamination, air pollution, and the escape of climate-warming methane gas. In recent years, a number of peer-reviewed studies have suggested that earthquakes are another potential side effect.

In fact, these studies show fracking is far from the only culprit for man-made quakes. In a 2012 article in the Journal of Seismology, Klose identified 92 human-induced earthquakes triggered by mining, dam building, and other kinds of industrial development. This new line of research is opening a window on the risks of human activities that can shake the Earth’s crust thousands of metres below our feet.

Until recently, the idea that humans could induce damaging earthquakes sounded, even to many scientists, like something from a bad science fiction movie. Sure, anything people do that makes the ground vibrate is technically an earthquake, but there’s a world of difference between the rumble of a passing freight train and an earthquake big enough to knock down buildings.

"Four years ago, when I used to talk about induced earthquakes, people used to stand up and say, ‘we don’t believe that humans can cause earthquakes’," says Cliff Frohlich, an earthquake seismologist at the University of Texas, Austin.

A case in point is the worst earthquake in Australia’s history, a magnitude 5.6 jolt that struck Newcastle, New South Wales, in 1989 leaving 13 dead, 160 in hospital, and $4 billion in property damage. But as recently as 2006, when Klose, then a geophysical hazard researcher at Columbia University’s Lamont-Doherty Earth Observatory, argued that this had been caused by 200 years of coal mining, the idea drew derisive snickers on the internet.

Then, last July, induced earthquakes made headlines following a trio of studies published in the journal Science. To those whose
views had been dismissed, it was long-overdue recognition. “It’s not news to earthquake scientists,” says Frohlich. “Seismologists have known this since the 1930s.”

That’s when construction was completed on America’s Hoover Dam, near Las Vegas. The dam created Lake Meade, still the largest reservoir in the US, capable of holding 37 cubic kilometres of water. That much water weighs a lot: 37 billion tonnes, to be precise. So perhaps it shouldn’t have been a surprise when seismometers in the area began recording earthquakes, up to magnitude 5.0, linked to the level of water in the lake.

None of the Hoover Dam earthquakes were damaging, but the residents of western India weren’t as lucky following the completion of the 103 metre-high Koyna Dam in 1964. Three years afterward, the area was struck by a magnitude 6.7 temblor that flattened a nearby village, killing an estimated 180 people and injuring 1,500 more. It’s the largest human-caused earthquake that “everyone agrees on”, says William Ellsworth, a seismologist with the US Geological Survey in Menlo Park, California.

But even that earthquake may not be the granddaddy of all. In 1976 and 1984, Uzbekistan’s Gazli oil field was hit by two magnitude 7.0 quakes that may have been produced by underground stress changes from decades of oil and gas extraction. “The scientific evidence doesn’t make a bulletproof case,” says Ellsworth, who is author of one of the recent articles in Science, ”but I think it’s likely.”

The granddaddy of man-made earthquakes might have been the magnitude 7.9 disaster that struck China’s Sichuan Province near Zipingpu Dam in 2008, killing 69,000 people and leaving another 18,000 missing. In a paper presented that autumn at a meeting of the American Geophysical Union in San Francisco, California, Klose argued that the pile-up of water in the reservoir might have over-stressed the fault, accelerating natural tectonic pressures by hundreds of years. And even in places where there are no contemporary tectonic stresses to be accelerated, the underlying rocks may still be under residual stress from ancient forces that never dissipated. “These faults just need something to trigger them,” Klose says, “and if human action is large enough it can break them.”

But it took a massive surge in earthquakes in the American heartland to bring human-induced earthquakes fully to public attention.

One startling bit of information from Ellsworth’s own Science article, tabulates earthquakes in the US midcontinent since 2001. In that short time, he found, there had been nearly a tenfold increase in the frequency of magnitude 3.0 or larger earthquakes from 21 per year to 188 per year, with most of the rise during the past four or five years.

It’s a change, Ellsworth says, that strongly parallels the increased use of injection wells, in which fluids are forced into the ground, often in conjunction with fracking. In fact, says Nicholas van der Elst, a seismologist at Columbia University’s Lamont-Doherty Earth Observatory, and lead author of another of the studies in Science, at least half of the largest of these midcontinent earthquakes (magnitude 4.5 or larger) came near such injection-well sites.

Not that this categorically proves that oil and gas extraction is the cause of any given earthquake. The US has a great many oil and gas fields, Van der Elst notes, which means the geographic proximity of earthquakes to oil and gas fields may simply be coincidence. “But it is suggestive,” he says. And despite the scientific caveats, the oil and gas industry is not trying to play down links or concerns. “The risk is known,” says Dana Bohan, a spokesperson for Energy In Depth, an arm of the Independent Petroleum Association of America. “It’s constantly being studied.”

Ironically enough, efforts to extract clean geothermal energy from the ground, instead of oil and gas, can also trigger earthquakes. In 2006, the Swiss attempted to develop geothermal resources beneath the city of Basel. In the process, they used high-pressure fluids to fracture non-
porous rocks to create gaps in which water could circulate for geothermal heating. But they got an unpleasant side effect: four magnitude 3.0 earthquakes, large enough to do minor damage. “They shut the project down,” Ellsworth says.

Tapping geothermal energy in more remote areas, such small earthquakes aren’t a concern, but seismologists still worry about the prospect of bigger ones.

In the third of the trio of articles in last July’s Science, Emily Brodsky, an earthquake physicist at the University of California, Santa Cruz, examined earthquake rates at California’s Salton Sea Geothermal Field. In part, she picked that study site because California requires geothermal plants to maintain good public records of their operations. But she also picked it because the Salton Sea is a lake near the southern end of California’s infamous San Andreas Fault, where induced earthquakes might pose a particularly large hazard.

Geothermal energy production begins by pumping superheated water from deep underground, and letting it flash into steam to drive turbines. The steam is then condensed back into water, which is re-injected into the ground. In theory, it’s a closed loop. In practice, some of the steam is inevitably lost to the atmosphere. In other words, less water is pumped back into the ground than was initially extracted.

What Brodsky found surprised her. With injection wells used for fracking, earthquakes appear to be triggered by shoving excess water into the ground. If asked in advance, she would therefore have expected earthquakes from geothermal energy production to correlate most strongly with high levels of operation, where large quantities of water are being both drawn out of the ground and injected back into it. But here, they seemed to be linked to the amount of water being lost via escaping steam: in other words, the net rate at which water was being pulled out of the ground without replacement.

How can it be that totally opposite activities — injection of water in one case, withdrawal in another — can each induce earthquakes? The answer begins with a basic understanding of earthquake processes.

Earthquake faults are simply cracks that are subjected to forces (called shear forces) that make one side want to slide against the other. The only reason the fault doesn’t slip instantly is that other forces clamp it too firmly together. You could compare it to pressing your palms against each other while also trying to slide them sideways. Ellsworth compares it to a brick on a tilted board; the brick remains in place until you tilt the board so far that the brick starts to slide.

“A fault will remain silent, not moving, until the shear stress exceeds the stress clamping it together,” he says.

As with your hands, or the brick, there are three basic ways to make it move. One is to increase the shear stress, as tectonic forces slowly do in traditional earthquake zones. But you can also make it slip by reducing the clamping pressure, or lubricating the fault with something slippery.

Human-triggered earthquakes probably work by all three mechanisms. In the case of China’s Sichuan earthquake, for example, Klose estimated that 320 million tonnes of water piled up behind the dam in the two years before the quake. That’s far less than in Lake Meade, but still enough to produce a substantial change in shear forces across the fault.

Something similar might have happened at Newcastle, Australia, though in that case it would have been the removal of weight that was...
the culprit. In his 2006 study, Klose estimated that for each tonne of coal extracted from the mines, another 4.3 tonnes of groundwater had to be pumped out in order to prevent flooding. Multiply that by 200 years of operation, and it’s a big change.

Long-term extraction at oil and gas fields like Gazli might also induce weight shifts, in this case possibly including the effect of groundwater replacing natural gas in the rock pores. And Brodsky thinks something similar might be at work in the Salton Sea Geothermal Field, though in this case, she suspects that the culprit might not be simply due to mass removal but changes in stresses due to compaction of the deep strata when all of the water withdrawn from them is not returned.

A third way to induce earthquakes is by injecting water into the ground, thereby increasing the fluid pressure in the rock’s pore spaces – in essence lubricating nearby faults and allowing the rocks to slip more easily.

That last mechanism isn’t just a theory. In a July 2013 article in the Journal of Geophysical Research: Solid Earth, Won-Young Kim of Lamont-Doherty Earth Observatory found a correlation between earthquakes (up to magnitude 3.9) near Youngstown, Ohio, and fluid injection activities at a nearby well. There’s even more compelling evidence. All the way back in the 1960s and 1970s, the US Geological Society (with oil-company co-operation) tested the theory in Chevron’s Rangely Oil Field in northwestern Colorado, where fluid injections were being used to force oil from aging wells. Working in a portion of the field where small earthquakes were common, the researchers found that by varying the pressure of the fluid being injected, they could very easily turn the area’s seismic activity on and off.

For the energy industry it’s a tantalising result – a hint that by modulating fluid injection activity, they might avoid serious earthquakes altogether. “One of the Holy Grails is to make some connection between what an operator might choose to do, like pump fluid out of the ground or into the ground, and how many earthquakes are the result,” says Brodsky.

In the Rangely experiment, the scientists were able to produce such dramatic results in part because they had detailed information about subsurface conditions, allowing them to calculate the fluid pressures that might be critical.

But that’s rarely the case, and the data is expensive and time-consuming to gather. Another problem is that studying earthquake rates isn’t the same thing as figuring out how big the earthquakes are likely to be.

In general, earthquakes follow a simple scaling law, with small ones being vastly more common than large ones. The power of the largest, and rarest, is limited by the size of the fault system.

On small faults, that’s reassuring. But not on big ones, such as the San Andreas Fault near the Salton Sea facility studied by Brodsky. “The chances of making a truly enormous, damaging earthquake are quite low, but not zero,” she says.

Ellsworth adds that there’s a potential for even modest-sized induced earthquakes to do significant damage if they happen in the wrong place. The 2011 earthquake in Sparks, Oklahoma and the Newcastle quake, for example, were comparable to a naturally caused magnitude 5.7 earthquake that occurred in 1986, directly beneath El Salvador’s capital city of San Salvador. The El Salvador earthquake killed between 1,000 and 1,500 people, injured another 10,000, and left 200,000 homeless.

For earthquakes induced by dams and giant mines, hazard analysts only have to collect data from a limited number of sites. But a boom in fracking has made the process exponentially more difficult.

Happily, fracking itself has never directly produced an earthquake larger than magnitude 3.6, Ellsworth says. The larger earthquakes, such as the one that hit Sparks, Oklahoma, appear to come from re-injecting polluted fluids produced by the process back into the ground.

“It’s related to fracking, because the wastewater is caused by fracking operations,” says Frohlich, “but you’d have the same problem if you pumped tap water into the wells.” That’s actually good news for the industry, he adds, because this wastewater doesn’t have to be re-injected. It can be treated like sewage, cleaned up and disposed of on the surface.

Another piece of good news is that not all injection wells produce earthquakes. Frohlich notes
that Texas alone has more than 10,000 wells. “If it were a severe hazard, Texas would be famous for earthquakes,” he says.

Nor are tiny earthquakes in remote locations, like those induced by the US Geological Society’s Rangely tests, likely to be a hazard. What’s needed is a way to determine which wells might be on the verge of producing bigger quakes, closer to civilisation.

Columbia University seismologist van der Elst believes that part of the answer may be supplied by using giant, far-away earthquakes, such as those that recently struck Sumatra, Japan and Chile as probes. Such earthquakes, he says, send waves across the entire surface of the Earth. Usually, these ripples have no effect. But in a few cases, they produce swarms of small earthquakes, swarms that could highlight locations ripe for bigger earthquakes in the near future. In other words, earthquakes triggered by far-away giant temblors might serve as warning signals that an injection-well zone is on the verge of overloading its nearby faults.

In his own paper in Science last year, van der Elst put this to the test by searching seismic records for clusters of remotely triggered tremors at injection-well sites that later had sizeable earthquakes. What he found was that sometimes they occurred, sometimes they didn’t.

No such warnings, for example, preceded a magnitude 4.7 earthquake in Guy, Arkansas, a magnitude 4.7 earthquake in Jones, Oklahoma, or a magnitude 4.0 earthquake near Youngstown, Ohio. But they indeed appeared prior to three magnitude 5.0-plus earthquakes in Oklahoma (including the one in Sparks), as well as a magnitude 4.3 tremor near Snyder, Texas, and a magnitude 5.3 quake near Trinidad, Colorado. What this meant is that van der Elst had found a simple screening tool to help seismologists focus their attention on at least some of the potentially dangerous areas. The tool can be applied whenever a giant earthquake strikes any part of the globe.

Not that such a warning would come in time to prevent the drilling of wells or building of dams in dangerous zones. But they could give operators and regulators a heads-up to impending danger, allowing them to take steps to fend it off. For dams, these steps might take the form of draining the reservoir pending further study. For injection wells, the simplest action might be to curtail pumping until risks are better known.

All told, it’s a far cry from the days when Frohlich was being scoffed at for even suggesting that human-induced earthquakes were possible. But this newfound agreement doesn’t have to mean a death-knell to fracking, geothermal energy, or other types of injection wells. “The bottom line,” says Ellsworth, “is that there is a risk from injecting fluids underground, but it is a risk that can be managed.”

As well as monitoring ripples from distant earthquakes, careful observation at individual oil fields can give subtler, localised warnings that injection-well fluids might be starting to affect a fault, says Wong, the Oakland consulting seismologist. Dangerous earthquakes are generally preceded by smaller seismic events. With this type of monitoring, Wong adds, it’s possible to create a “traffic-light system” for risk minimisation: “If [seismic activity] is green you’re OK. If it’s yellow, you’d better start paying attention. And if it’s red, stop.”