Seismic boom

Imagine a rupture that travels along a fault line so fast it overtakes its own shock waves. **Richard Fisher** investigates

THE convoy was more than 30 kilometres from the Kunlun fault in Tibet when the jeeps suddenly lurched. They had hit a series of parallel cracks, remnants of a magnitude 7.8 earthquake that struck the year before. "It was like driving on steps," recalls Yann Klinger, a geologist from the Paris Institute of Geophysics in France.

The cracks were clear signs that the ground had been squeezed like a sponge then released, violently wrenching it apart. Yet they were much too far from the fault line to be explained by the quake. Mystified, the team took some measurements and moved on.

It transpired that Klinger and his team had stumbled upon the aftermath of a "supershear" earthquake – one that slipped at such blistering speeds that the rip in the Earth overtook its own seismic waves. This created the earthquake equivalent of a sonic boom, capable of striking anything in its path like a hammer blow. While some seismologists had suspected such a quake could happen, physical evidence of their power had been lacking.

Seven years on, and the evidence is mounting that these kinds of earthquakes may be more common than we thought, and not just in remote regions like Tibet. A series of new maps reveals an abundance of so-called "superhighway" faults around the globe where the conditions are just right for earthquakes to zip through the ground at great speed. Worldwide, 60 million people live in these zones – many of them in regions that were not previously considered at risk from

ERSOY EMIN/ALAMY

earthquakes. And even in places where buildings are designed to cope with the biggest quakes, no one knows if they will be able to withstand a supershear.

Until supershear quakes came on to the scene in the late 1990s, earthquakes were thought to come with an inbuilt speed limit. When a fault slips at a weak point, the break propagates along the fault line. Mathematical equations show that ruptures cannot propagate at speeds in a so-called "forbidden zone", between around 3 and 3.5 kilometres per second. At these speeds, the fault's frictional sliding would have to convert heat into mechanical energy – something that is thermodynamically impossible. Since a rupture can never accelerate through this zone, the possibility of quakes faster than 3.5 kilometres per second was ruled out.

Supershear quake hits Izmit in Turkey in 1999

For many years only one observation contradicted this received wisdom. In 1984, Ralph Archuleta at the University of California, Santa Barbara, reported that the Imperial valley earthquake that struck California in 1979 briefly ruptured faster than 3.5 kilometres per second, the speed that a type of seismic wave called a shear wave travels at (*Journal of Geophysical Research*, vol 89, p 4559).

With only indirect evidence that this "supershear" earthquake had occurred, however, plus the mathematical unlikeliness that it had taken place and a lack of any other reports of earthquakes moving at such incredible speeds, the paper was largely dismissed. "That observation did not go down very well with seismologists," says Ares Rosakis at the California Institute of Technology in Pasadena.

Archuleta's observations languished in obscurity for nearly two decades until a wager between an engineer and a geologist meant that they were finally tested out in the lab.

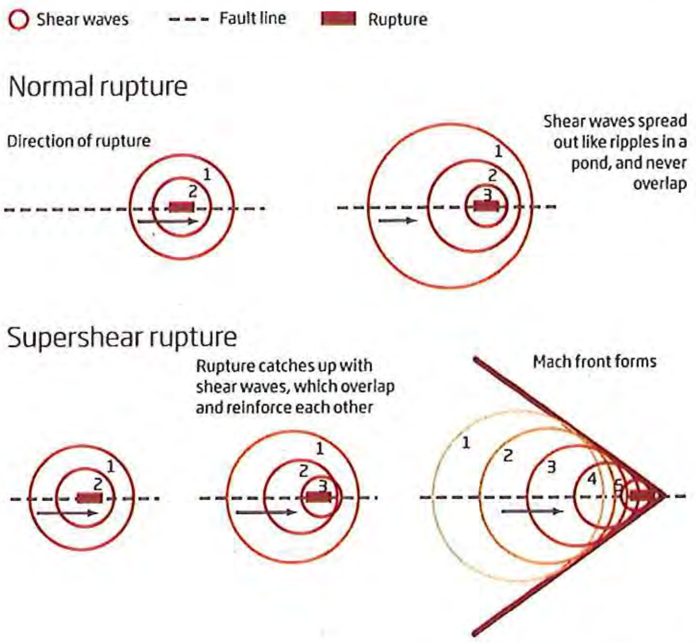
Rosakis had studied the dynamics of ruptures in other settings, such as artificial materials. In previous experiments funded by the US navy, he had been investigating how explosions affect materials that have been glued together, and had seen supershear ruptures occur along the glued interface. So why not in the Earth itself? His sceptical colleague Hiroo Kanamori, in the geology department at Caltech, disagreed. After all, a fault under pressure is nothing like a glued surface and earthquakes are not triggered by explosions. The bet was set – an expensive bottle of wine was at stake.

To simulate an earthquake, Rosakis and Kanamori took two slabs of a polymer that transmits light when under pressure and pressed them together, the join representing a geological fault. They shone a light through the fault zone and then triggered a tiny electrical pulse to produce a rupture along the fault line. The patterns made by the light allowed them to see the seismic waves produced as the rupture moved through the fault. Sure enough, the quake produced seismic waves – first compressional waves, followed by the shear waves. And as Kanamori had predicted, the rupture itself trailed well behind its seismic waves.

With Rosakis on the verge of losing the bet, they put the slabs under slightly higher pressure by squeezing the fault tighter. Then, when they triggered a rupture, something odd happened: a fresh "daughter" crack suddenly appeared ahead of the main "mother" rupture, travelling much faster. The daughter crack then expanded rapidly, and joined up with the mother rupture, causing the entire rupture to immediately start travelling faster than its shear waves, leapfrogging the "forbidden" speeds. Not only that, it continued to produce new shear waves, which added to the first batch to produce a new, more powerful shock wave called a "Mach front", which trailed behind the rupture in the shape of a boat's wake (see diagram, below) (*Science*, vol 303, p 1859). This is similar to what happens when jet fighters break the sound barrier ›

Making of a Mach front

When a rupture moves down a fault line faster than shear waves can escape, these waves combine and propagate as a powerful and destructive Mach front



Shear waves spread out like ripples in a pond, and never overlap

Rupture catches up with shear waves, which overlap and reinforce each other

Earthquake "superhighways"

Living near a fault line is bad enough, but the ones below may rupture at "supershear" speeds, potentially increasing the range and ferocity of the quake

Dead Sea, Jordan/Israel
2 superhighway sections
Fault length
1000 km
5.2 million
people within 50 km

Altyn Tagh, Tibet
3 superhighway sections
Fault length
1200 km
62,000
people within 50 km

Kunlun, Tibet
4 superhighway sections
Fault length
1600 km
150,000
people within 50 km

Red River, Vietnam/China
3 superhighway sections
Fault length
1000 km
25.7 million
people within 50 km

Chaman, Pakistan/Herat, Afghanistan
3 superhighway sections
Fault length
1100 km
2.5 million
people within 50 km

Denali, Alaska
1 superhighway section
Fault length
1400 km
Negligible
people within 50 km

Luzon, Phillipines
1 superhighway section
Fault length
1600 km
2.1 million
people within 50 km

San Andreas fault, California
2 superhighway sections
Fault length
1050 km
13.1 million
people within 50 km

Bulnay, Mongolia
2 superhighway sections
Fault length
300 km
20,000
people within 50 km

Sagaing, Burma
1 superhighway section
Fault length
1000 km
9.1 million
people within 50 km

Great Sumatra
4 superhighway sections
Fault length
1600 km
6.7 million
people within 50 km

and travel at Mach speeds; they create pressure waves as they speed through the air, but travel fast enough to catch up with them. The waves constructively interfere with each other to become one explosive sonic boom, extending in an expanding cone behind the aircraft.

Shaking all over

These lab experiments began to show that earthquakes could, in theory, go supershear. But it was the Earth itself that provided the real-world evidence. In 1999, the most seismically active continental fault of the 20th century – the North Anatolian fault in Turkey – slipped to cause the magnitude 7.6 Izmit earthquake. Unlike the California quake of 1979, this time there was no shortage of seismic stations around the fault to record the speed of the shear waves produced in the quake. Measurements of ground motion also provided evidence of the speed at which the fault ruptured. It all added up to a quake that went supershear, says Michel Bouchon at the University of Grenoble in France, who led one of two teams that independently showed that Izmit reached velocities of up to 5 kilometres per second (*Geophysical Research Letters*, vol 28, p 2723).

Now there was no longer any denying that, both in theory and practice, earthquakes can go supershear and seismologists around the world set about looking for more examples in the aftermath of new quakes. They found plenty. There is now evidence that at least three major quakes around the world since Izmit have gone supershear, including Kunlun, where Klinger's team had found the then-mysterious cracks. Thankfully, there have only been a handful of such quakes recently and most have been in remote areas.

This will not always be the case, of course. Some geologists suspect that the devastating San Francisco earthquake of 1906 may have been a supershear. Gregory Beroza of Stanford University in Palo Alto, California, and colleagues argue that such a rupture would explain a long-standing mystery. We know from ground measurements that the crust slipped a certain distance, but seismic data recorded by distant stations showed that the earthquake did not last long enough to produce displacement over such a distance. However, a rupture travelling at supershear speeds would have torn through the ground much faster, producing the observed rip in a shorter time than a normal quake (*Bulletin of the Seismological Society of America*, vol 98, p 823).

Understanding earthquakes after the event is only half the battle, however. What everyone wants to know is where the next one might hit. Now seismologists David Robinson, Shamita Das and colleagues at the University of Oxford think they have come up with an answer. They compared known supershear quakes for similarities and used these to try and anticipate where in the world the next one is most likely to strike.

The only faults shown to have generated supershear quakes so far have been "strike-slip" faults, where bodies of rocks rub by each other laterally, with very little vertical movement. For this reason, Robinson figured that other kinds of faults, where bodies of rock slide over one another, for example, could be ignored. Next, he discounted ocean-based strike-slip faults as none have so far been found to have reached supershear speeds, plus they are unlikely to pose significant danger to populations. The main risk of an ocean quake is a tsunami, but strike-slip faults tend not to create them because they do not cause the significant uplift of the

"Regions thought to be beyond the reach of an earthquake may be caught unawares by a supershear earthquake"

ocean floor typically needed for a tsunami.

That still left a huge number of strike-slip faults on land to sift through. But Robinson reasoned that all of the supershear ruptures seen so far have been on long, straight sections of faults. This might be because a rupture cannot accelerate to supershear speeds on a convoluted fault path. "We liken it to driving along a road," he says – the rupture slows down for corners, like a car during a turn. So based on previous theoretical modelling and the straightness of known supershear faults such as Kunlun, Robinson looked for unbroken faults on land that do not deviate by 5 degrees or more over a distance of 100 kilometres. That narrowed it down to 26 sections on 11 different fault systems around the world, including parts of the San Andreas fault in California (see map, left). He called them "superhighways".

Worryingly, when they added the population distribution within a 50-kilometre radius of these faults, they found a network of superhighway faults primed to rumble near major cities. Seven of the 26 superhighways lie within reach of heavily populated areas, each potentially affecting more than 2 million people. One runs straight through the middle of San Francisco, while the cities of Rangoon and Mandalay in Burma sit at either end of the longest superhighway. "The density of population in some areas of Asia we looked at is incredibly high. That really surprised me," says Robinson, who presented his findings at the Seismological Society of America's annual meeting in April.

The maps were welcomed by geologists. "Robinson's work is excellent," says Bouchon. "The supershear earthquakes we have observed up to now have always occurred on long strike-slip faults with very linear segments and simple geometry," he says. Rosakis, however, points out that the roughness of the fault interface and the fault's inclination could also play a part. "It would, to my mind, be too simplistic to say that [long and straight faults] are the only characteristic," he says.

For his part, Robinson concedes that his maps are only intended to scratch the surface. There may be other conditions in which supershear quakes could occur, he says.

Danger zone

If Robinson's maps are correct, it could mean that regions previously thought to be outside of the worst effects of an earthquake, and maybe even beyond its reach altogether, could be caught unawares by a supershear quake. The Mach front's high amplitude means that it travels further through the ground than normal shear waves, putting millions more people at risk.

The most recent building rules in the US, established in the late 1990s, place tight restrictions on the design of structures within 5 kilometres of an active fault. That's because these regions are considered vulnerable to the so-called "near source pulse" of an earthquake, says Swaminathan Krishnan of the earthquake engineering simulation group at Caltech. But with a supershear quake, many relatively unfortified buildings outside the 5-kilometre zone in, say, San Francisco or parts of Los Angeles, could also be at risk, says Krishnan.

Mach fronts also shake the ground differently to an ordinary earthquake, and that means current building standards may not be enough, even in well-prepared areas like California. Laboratory experiments suggest that the shock front strikes with greater ferocity than typical seismic waves. Buildings would experience all the force of the quake's accumulated shear waves at once. If an individual seismic wave is a "gentle slap", the Mach front is a "big hammer", explains seismologist Harsha Bhat of the University of California, Los Angeles. "It's a sudden impact hitting on a structure."

Recent work by Bhat and Eric Dunham of Stanford University also suggests that a building would be struck by two Mach fronts in rapid succession – one from the shear waves, followed by another made up of accumulated Rayleigh waves, a type of seismic wave that travels along the surface at around 3 kilometres per second. "It's still too early to say which Mach front is more devastating," says Bhat.

Unfortunately, most city planners and civil engineers are unlikely to take heed of the warnings of seismologists based on laboratory experiments. "Engineers are practical animals," says Krishnan. "We don't yet have enough data to support these theories."

That's why Krishnan is currently embarking on a project with Rosakis to simulate in a three-dimensional computer model what happens to buildings of various sizes as they are struck by a Mach front. "If our modelling shows serious issues, it will generate a lot of discussion," he says. However, Dunham points out that the smoking gun that Mach fronts are killers will come from a real quake. "Observations would be the most definitive," he says. "To really nail this down, you need lots of seismic stations fairly close."

What is needed now is more data on actual quakes that go supershear. As geologists wait for the next big one to strike, however, they are hoping that they will be proved right in an uninhabited desert – and certainly nowhere near a big city. ■

HOU DEQIANG/XINHUA

Ripped apart at seemingly impossible speeds: the Kunlun fault in Tibet

---

Richard Fisher is *New Scientist*'s deputy news editor