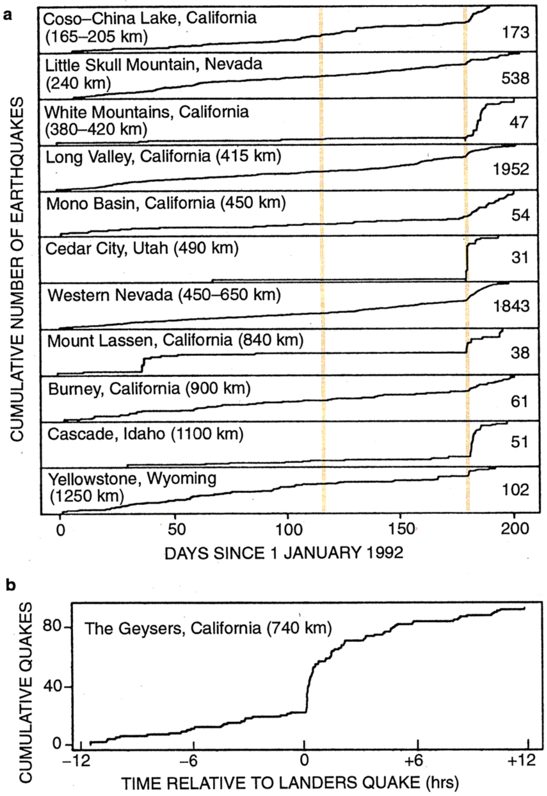
EARTHQUAKE YIELDS FIRST REAL EVIDENCE OF REMOTE TRIGGERING

Just before dawn on 28 June last year, the Mojave Desert 200 km east of Los Angeles was struck by a magnitude-7.3 earthquake. Although the Landers earthquake, named for the small town nearest the epicenter, was stronger than the earthquake that had rocked San Francisco three years earlier, it attracted little public attention, because the region is so sparsely populated. But it made seismological history. The dense and extensive network of seismographic stations built up in the Far West during the 1980s has provided convincing evidence that the Landers quake triggered secondary tremors as far away as Yellowstone National Park, 1250 km to the northeast.

These remotely triggered secondary events, at 14 locations in five Western states, represent something quite different from the usual aftershocks that routinely follow large earthquakes.

The initial event was the most powerful earthquake to hit Southern California in 40 years. Propagating northward from the epicenter into the Mojave Desert along a preexisting series of faults, the rupture produced slippages as large as 6 meters over a total length of 74 km. That 74-km extent is called the source length L of the initiating earthquake. It is the basic scaling parameter for any discussion of the distances to secondary seismic events. Ordinary aftershocks always occur within about 2 source lengths of the initial earthquake. By contrast, the typical remote site set off by the Landers earthquake was 6 or 7 source lengths from the original rupture line, and the most distant of them, the Yellowstone site in Wyoming, was fully 17 source lengths away.

Dozens of talks about the Landers earthquake and its seqeulae were heard at the American Geophysical Union's San Francisco meeting last December. A comprehensive report and analysis was recently published by David Hill (US Geological Survey, Menlo Park, California) and collaborators from 16 institutions in the Western states and Mexico.1 The greatest increase in seismic activity after the Landers quake occurred, of course, within 100 km of the initial rupture. But the paper passes over these nearby tremors as conventional aftershocks, to concentrate on events more than 2 source lengths away.



Evidence of remote triggering is seen in these plots of the cumulative number of earthquakes vs time at 12 sites in the western US. Distances from the Landers quake are shown in parentheses. In **a**, colored lines indicate the 25 April, 1992 Mendocino earthquake, which had no obvious effect, and the comparably strong Landers earthquake of 28 June, which triggered the abrupt onset of increased activity at all these sites. The numbers at right are the total number of quakes to the top of each plot. The accumulation of earthquakes at the Geysers, a geothermal field north of San Francisco, is shown in **b** for 12 hours before and after the Landers quake.

Conversion of the skeptics

Throughout the century, occasional incidents of large earthquakes followed within hours (or even minutes) by seismic activity far away have led to suggestions of remote triggering. But the evidence was always very tenuous. Because these incidents never involved more than a single site of alleged secondary activity, seismologists could, and did, dismiss them as coincidence. There are, after all, lots of little earthquakes going off all the time in seismically active areas. For example, one of the Nevada sites triggered by the Landers quake had 58 little tremors in the week *before* 28 June. (That has to be compared with 504 during the next week.)

The Landers data, recording unmistakably abrupt increases in seismic activity at 14 distant sites in the immediate aftermath of the big earthquake, have forced upon the seismological community the first evidence for remote triggering that cannot be explained away as coincidence. (See the figure on page 17.) But why were seismologists so reluctant to entertain the notion of remote triggering? The answer, aside from the absence of compelling data, has much to do with the widespread success of models that treat the Earth's crust simply as a linear elastic medium. Such models are very good at calculating the static strain fields that are created by large dislocations at fault lines. And they do just as well with the propagating compressional and shear waves that are the principal dynamic consequences of earthquakes. Using linear elastic models, seismologists have exploited the seismic waves unleashed by large earthquakes to map the Earth's interior in impressive detail. One knows about the liquid core of the planet, for example, because compressional waves can propagate in liquids but shear waves can't.

The static strain field created by an earthquake dislocation plays an essential role in the production of conventional aftershocks. But static strain falls off with distance d from the fault dislocation approximately like $(L/d)^3$. Before one gets as far away as $d=4L$, the static strain will have dwindled to less than the daily strain swing caused by tidal forces, even for dislocations as great as the Landers rupture. So it's hard to imagine that the static strain responsible for nearby aftershocks could also be triggering seismic events much beyond 3 or 4 source lengths from the original quake.

What about the *dynamic* strain that propagates away from the original rupture in transient seismic waves? In addition to the compressional and shear waves that propagate through the body of the Earth, there two modes of transverse surface waves that propagate only along the Earth's crust: The so-called Love waves are horizontally polarized shear waves with no compressional component, and the Rayleigh waves, which have both shearing and compressional components, are polarized normal to the Earth's surface. The Earth's crust goes down about 10 or 20 km. That's also the typical wavelength of the surface modes.

The surface waves, in particular, might be thought good candidates for remote triggering, because they fall off with distance more slowly than the body waves, and much more slowly than the static strain field. The problem is that these transient oscillatory perturbations produce no net effect in a linear elastic model. The direction of the strain keeps oscillating back and forth with a period on the order of 10 seconds as a seismic wave train goes by. If the passing waves are to play a role in triggering a secondary fault dislocation, they must provoke something more than just linear elastic oscillations.

Nonlinearity

The sudden rupturing event that initiates an earthquake is, of course, nonlinear. But when seismologists speak of linear vs nonlinear mechanisms in this context they are referring to changes that predispose a fault to suddenly slip by weakening it or increasing its stress. Before the Landers earthquake shook up the conceptual landscape, relatively little attention was given to possible nonlinear mechanisms for triggering secondary earthquakes.

The time delays between the Landers quake and the onset of activity at the various remote sites are also suggestive of nonlinear triggering mechanisms. The delays range from 3 minutes at the Geysers, a geothermal field just north of the Napa Valley, to 33 hours at a site in the Cascade Mountains of Idaho. The seismic activity at the Geysers began just 30 seconds after the arrival of the body shear wave (the so-called S wave, which travels through the Earth at about 4 or 5 km/sec) from the Landers quake. But at the majority of the secondary sites no local activity was observed for at least an hour after the last of the Landers wave trains had passed through.

Such long delays between cause and effect suggest to Hill and his coauthors that the movement of underground fluids is somehow involved in these nonlinear triggering mechanisms. All of the observed remote triggering events occurred in areas of known faulting and persistent seismicity. On the other hand, the notorious San Andreas fault and a number of other areas well known for seismic activity showed no response to the Landers earthquake. Most of the remote areas that did respond are known for geothermal activity or recent volcanism. ("Recent," in this context, means the last million years.) That points to magma (molten rock) and water, possibly superheated water, as obvious fluid suspects.

Faults are generally weakened when fluid is introduced into or around them, or when the pressure of a fluid already present is increased. It has often been observed that passing seismic compression waves can make the water level fluctuate wildly in a well that taps a porous aquifer. "It's like squeezing a sponge," Hill told us. These pore-pressure pulses might simply weaken a fault to the point of snapping. Hill and his coauthors also suggest more indirect mechanisms that would explain the longer delays. The pressure pulses, they point out, might rupture seals between previously isolated porous fluid volumes with different hydrostatic pressures. After the resulting transfer of water, whose speed would depend on things like permeability and pressure gradients, a fault might find itself immersed in a much higher static pore pressure than it previously had to endure.

Similarly in volcanic regions, where magma can be within a few kilometers of the surface, passing seismic waves from a distant earthquake might weaken local faults by forcing magma up into them. The passing waves might also force dissolved gases out of the magma, or they might increase the liquefaction of partially crystalized magma. Any of these effects, the authors speculate, could unleash local quakes.

Is remote triggering common?

If the Landers earthquake and its far-flung offspring had erupted much before 1980, the remote triggering would probably have gone unnoticed, or at least unverified, because the network that now gives the Far Western United States the most intensive seismographic coverage of any large region on Earth was not yet substantially in place. Most of the activity triggered by the Landers quake was, after all, unobtrusively weak (magnitude less than 3) and remote.

But Landers was by no means the first large earthquake in the region since the network began its full vigil. The Western states had experienced four other quakes of magnitude around 7 since 1980. In addition to the famous Loma Prieta earthquake of October 1989, named for a modest mountain near its epicenter 50 miles south of San Francisco, there was a large quake in the mountains of Idaho in 1983 and two near Cape Mendocino on the northern California coast. The last of these occurred just two months before the Landers quake. None of these four large, well-documented earthquakes appears to have triggered any remote seismic activity, with the possible exception of some very minor activity at the Geysers,

The two days following the great San Francisco earthquake of 1906 saw eight significant quakes within 700 km of the city. But the source length of that historic quake was an extraordinary 300 km. Therefore one could classify those events as conventional near-field aftershocks.

With so few examples in hand of big earthquakes documented in detail by extensive modern seismographic networks, it is difficult to estimate the probability that a large quake will induce remote triggering, or to say what the crucial factors are. But it is clear that remote triggering is far from inevitable. Much would seem to depend on the directionality of the seismic wave propagation, and perhaps its polarization, in relation to the surrounding geology.

Seismic wave propagation gets a kind of Doppler enhancement in the direction in which the primary rupture moves. That's north by northwest from the epicenter in the Landers case, pointing almost precisely along the margin between the Sierra Nevada mountain range and the Great Basin to its east. That geological boundary is a belt of "recent" faulting and persistent seismicity, and it is in fact the zone that experienced the greatest concentration of post-Landers remote triggering. In the two large Cape Mendocino earthquakes of recent years, by contrast, the propagation direction of the ruptures was out into the Ocean.

The various wave trains are broadened by velocity dispersion and scattering as they get farther and farther from the source quake. The velocity of the surface waves, for example, increases with wavelength. An observer at the site of a remote triggering will therefore have experienced each passing mode for considerably longer than the duration of the original earthquake. But within a quarter of an hour all the seismic wave modes have passed and it's quiet again—until the triggered event manifests itself.

This eerie respite makes it clear that the triggering is not driven solely by the dynamic stresses carried by the seismic waves. The triggering processes probably vary from site to site, depending on the local geology. In general the triggering at any one site produces an "earthquake swarm," a cascading failure sequence in a volume of crust that was already in a critical state of stress.

"The theory of earthquakes is still very primitive," says Caltech's Hiroo Kanamori. "The Landers example, with its clear evidence of remote triggering, has given us some guidance to new ways of thinking about what initiates seismic ruptures, both secondary and primary. It particularly calls our attention to fluids and nonlinear mechanisms."

What about societal implications? If Landers is typical, remote triggering has little relevance to the problem of early warning. All of the distant triggered events were too weak to do significant damage. The largest of them was a magnitude-5.6 tremor at Little Skull Mountain in Nevada. A quake of that size usually doesn't do much more than rattle teacups. "But Landers will give me pause the next time a reporter asks whether some large earthquake far away might have local consequences," Hill told us. "I always used to say 'Of course not!' But after Landers, I can't be so sure."

—BERTRAM SCHWARZSCHILD

Reference

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Stirring Things Up in Waste Tank at Hanford

At the Hanford Nuclear Reservation in Richland, Washington first steps are being taken toward mitigation of the threat posed by hydrogen buildup in a million-gallon tank of radioactive waste. Shown in the photograph is a 64-foot-high pump being lowered on 4 July through a 40-inch-diameter pipe into tank 101-SY, which is buried below ground. Of the 177 tanks of high-level waste stored at Hanford, 101-SY is the most notorious, because of the high concentrations of hydrogen that are produced by its mixture of radioactive materials and organic chemicals. (See PHYSICS TODAY, March 1992, page 17.) The material in the tank forms a viscous slurry at the bottom, covered by a liquid layer and topped by thick pieces of crust. As the hydrogen is generated, it is trapped in the slurry, and about every three months it is released in a giant "burp." Hydrodynamic models have indicated that the pump should be able to stir the tank contents enough to promote a continual release of hydrogen gas and prevent the accumulation of explosive concentrations.

The pump being used in the test was one that the Westinghouse–Hanford Company, which manages Hanford, had on hand to use in another facility. Carl Hanson, design manager for the hydrogen mitigation program told us that his group modified the pump so that it takes in liquids from near the center of the tank and discharges them through opposing jets near the bottom.

There has always been concern that any perturbation of the tank might ignite the high concentration of hydrogen. Thus the pump was lowered into place just days after a burp, when the hydrogen concentrations should be the lowest. The pump speed and operation time have been gradually increased, and by now the pump is running at 1000 rpm for five minutes at a stretch, twice a day.

In mid-August some workers conducting at test at the tank inadvertently started the pump; no damage was done, however. A week later there was an unrelated incident at another tank that resulted in radioactive contamination of some workers. The two breaches of safety procedures have prompted Westinghouse–Hanford to halt all nonessential work at the tank farm until managers, supervisors and operators are retrained to pay proper attention to safety.

The pump tests will continue. So far the pump is promoting the release of some hydrogen, and cameras within the tank have recorded motion of the liquid surface, but only further tests will reveal whether stirring the tank can release enough hydrogen to prevent worrisome concentrations. If so, then a pump will be designed especially for that task.

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