# Seismic Sunday

## Recent jolts boost southern California's hazard

By RICHARD MONASTERSKY

Landers, Calif., a sleepy town in the southeast Mojave Desert, doesn't seem a likely spot to earn mention in any history book. But June 28 changed this town's fate when a very large earthquake emanated from a nearby fault, indelibly etching the name Landers in the annals of seismology.

California earthquake experts had spent decades waiting for just such a tremor in their own backyards. With a magnitude of 7.5, the Landers shock was the largest to strike the state in 30 years, giving a whole generation of researchers their first chance to study a seriously strong jolt up close. Moreover, the earthquake hit a relatively unpopulated area, limiting the numbers of deaths and damage, which were surprisingly low for a shock of this size.

"We're all exhilarated by what we are finding," says Kerry E. Sieh, a geologist with the California Institute of Technology in Pasadena. "It's the sort of thing that I have spent most of my career trying to figure out from the prehistoric record. But to actually see it right there, fresh as a new wound, gives us a tremendous opportunity."

More than most seismic events, the Landers shock has the potential to teach a host of new lessons to scientists still struggling to learn the basic rules about earthquakes. At the same time, it has rattled researchers, who see the Landers quake as a possible herald of a great quake, the so-called "Big One."

Many residents awakened by the 4:57 a.m. shock must have wondered whether the "Big One" had finally come rumbling out of their nightmares. For years, California scientists have warned about the seismic hazard from the San Andreas fault, which forms the major boundary between the plate carrying North America and the one underlying the Pacific Ocean. Moving northwest at a rate of 47 millimeters a year, the Pacific plate grinds past North America, generating the stress that drives most California quakes. Indeed, evidence from past shocks on the San Andreas indicates that the southern end of this fault will eventually unleash a magnitude 7.5 or 8 quake that could kill thousands and wreak billions of dollars' worth of damage in the heavily populated Los Angeles and San Bernardino areas.

But when the shaking and rolling on June 28 subsided with little damage outside the epicentral region, it soon became evident that the "Big One" had not arrived. Although similar in strength to the forecasted San Andreas quake, the Landers shock emanated from distant faults in the sparsely populated Mojave Desert. Moreover, the strongest seismic waves raced northward, farther into the desert, instead of heading into the crowded basins to the west.

Three hours later, a magnitude 6.6 aftershock ruptured a different fault beneath the Big Bear ski resort in the San Bernardino Mountains, unleashing a second series of aftershocks. Over the next few hours, the two lines of aftershocks formed what resembled a large Greek lambda, with both legs resting on the San Andreas fault.

That proximity to the San Andreas worried seismologist Lucile Jones and her colleagues, who monitored the early morning activity at the U.S. Geological Survey (USGS) office in Pasadena. In fact, several aftershocks occurred on the San Andreas itself, where the legs of the lambda join the major fault, says Jones. None of them was large, but their very presence troubled the researchers. With several faults springing into motion on that Sunday morning, Jones and the other seismologists wondered whether the San Andreas would go next.

Sometimes, earthquakes on one fault will lower the stress on a nearby fault, reducing the hazard of another earthquake in that region. But southern Californians have no such luck in this case. The Landers and Big Bear quakes were oriented in such a way that they actually increased the stress threatening to cause a major San Andreas shock. At the same time, they reduced some of the force clamping the two sides of the San Andreas together, according to calculations made by Robert W. Simpson of the USGS in Menlo Park, Calif. Unclamping the San Andreas has reduced the friction on this section of the fault – in theory, making it easier for the locked San Andreas to move.

"Both of these [changes] would be conducive to having earthquakes on the San Andreas," Jones says.

With aftershocks on the San Andreas and the stress changes in that region, seismologists have plenty of reason to worry that the feared fault may soon act up. And the pattern of recent seismic activity around the San Andreas boosts the level of concern one notch higher. For 38 years prior to 1986, no earthquake stronger than a magnitude 5 occurred near the southernmost part of the San Andreas, known as the Coachella Valley segment. But something changed in the mid-1980s. In the past six years, this region has hosted six earthquakes above magnitude 6.

Seismologists readily admit they don't know what is causing the recent activity or where it may lead. But the pattern doesn't bode well.

"Just as a symptom, the fact that we're having all these earthquakes shows that something must have changed in the stress state so that these earthquakes could happen. Plus the earthquakes themselves are causing stress changes on the San Andreas fault that would be conducive to failure. So we've got to say that the hazard is up," Jones says.

Recent activity around the Coachella Valley lends credence to suggestions made in recent years that this segment is ripe to rupture, judging from the record of past earthquakes there. Trenches cut across this part of the fault by Sieh and his colleagues indicate that the segment's last four major ruptures occurred roughly 250 years apart, with the most recent one around 1680. Given that more than 300 years have passed since that jolt, the Coachella Valley would appear due for another one within the next few decades.

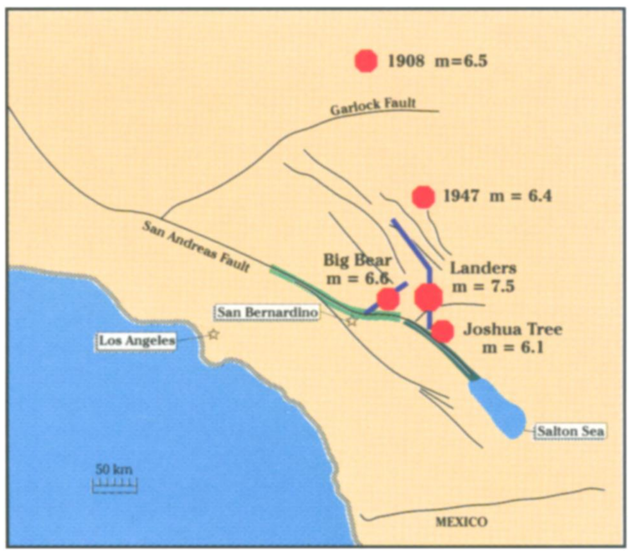
In a 1988 USGS report, a panel of earthquake experts estimated the probabilities of upcoming shocks on various sections of the San Andreas. Of all segments prone to large quakes, the Coachella Valley segment was judged as having the highest probability. The panel estimated a 40 percent chance that the segment would produce a magnitude 7.5 earthquake by the year 2018.

On its own, such a jolt might not prove tremendously destructive in this sparsely populated region. But the rupture could spread northward onto the next part of the fault, the San Bernardino Mountain segment, which runs right by the populous cities of Riverside and San Bernardino and lies closer to Los Angeles. If the quake spread even farther north to the Mojave segment, it would register a magnitude 8 and cause severe damage in the Los Angeles Basin and the San Fernando Valley.

Right after the Landers and Big Bear quakes, seismologists and state officials worried that a San Andreas earthquake might come within hours or days. Given that concern, California's Office of Emergency Services issued its most strongly worded earthquake warning to date, advising people to stay off freeways and curtail nonessential activity in San Bernardino and Riverside counties. But as the aftershocks died down over the day, the state rescinded the freeway notice.

By now, the immediate crisis has long since passed, and seismologists have shifted their concern to the next few months or years. According to one plausible scenario, the recent clustering of earthquakes since 1986 could be leading up to the expected temblor along the San Andreas sometime soon.

But that is by no means the only possible outcome. "Maybe all the energy was expended in this cycle and it turned out to be not quite enough to trigger the big one," Jones muses. In this second scenario, activity along the Coachella Valley would die down for a while. The major San Andreas quake would then wait until after another cycle started.




*The Landers and Big Bear quakes raised the risk of a shock on the Coachella Valley segment (dark green) and the San Bernardino Mountain segment (light green) of the San Andreas fault. The Landers shock aligns with quakes from 1947 and 1908, suggesting that a new fault could be replacing older northwest-pointing ones.*

As a science still in its infancy, seismology can't offer a clue to which of these two scenarios will hold true. In fact, neither may be right. The earthquake cycle could quiet down, to be followed years later by a San Andreas quake that strikes on its own, unheralded by any rise in seismic activity. Recent events, however, offer some hope that the Earth will provide a little advance warning.

The Landers quake was preceded by several hints of impending activity. Almost two months before, on April 22, a magnitude 6.1 tremor called the Joshua Tree quake originated on a southern section of the same fault that would later generate the 7.5 shock (SN: 5/2/92, p.293). Seismologists are now labeling the Joshua Tree quake a "precursory" shock to the main event.

Such precursory quakes appear something of a trend these days. In the 17 months preceding the magnitude 7.1 Loma Prieta quake of 1989, two magnitude 5 shocks occurred in the same area as the later mainshock (SN: 10/21/89, p.261). Farther north, where the San Andreas fault bends west into the ocean, a magnitude 6.9 earthquake this April was preceded by a magnitude 6 jolt in the same location eight months earlier.

Such relationships intrigue Jones. "We've had a lot of examples recently of these earthquake clusters on the time scales of months to years," she says, "and I would like to get into looking at that problem." She wonders whether the precursory earthquakes differ in any detectable way from other isolated quakes.

The same question applies to true foreshocks, which precede a larger quake by minutes, hours, or days. Like many earthquakes, the Landers temblor had foreshocks, as did the Joshua Tree quake.

In studies of past foreshocks, seismologists have not succeeded in detecting any discriminating characteristic that could serve as the basis for identifying which jolt precedes a larger quake. But the Landers and Joshua Tree events offer hope in that search, because they were captured by a network of new broadband seismometers, providing a highly detailed record of the fault rupture.

"We've got great data from this earthquake; we've got really high-quality waveforms that we've never had before," says Jones. "So there's gonna be lots of chances to get at some of those really fundamental questions in seismology, like how does an earthquake start and how does it stop. I think there are going to be [graduate] theses for years to come on these earthquakes."

Seismologists aren't the only ones harvesting data from the recent quakes. Geophysicist Amos Nur of Stanford University believes the Landers and Joshua Tree tremors may represent the birth of a major new fault that could eventually compete with the San Andreas.

Three years ago, Nur and his colleagues proposed that a new fault was forming in the Mojave to replace a set of aging faults. The older faults have apparently rotated over the past 6 million years, so that they no longer point in an optimal orientation to absorb stress created by the movement of the Pacific and North American plates. The Landers and Joshua tree quakes fall in the same line as four other quakes that have struck the Mojave in the last 50 years, suggesting that this 100-kilometer-long line may represent a new fault that could eventually take the place of the San Andreas, shearing off most of California, sending it inching toward Alaska.

With so much potential to answer fundamental questions, the Landers quake also poses new problems for earthquake experts. Because of the way it grew, this unexpectedly large shock raises questions about a technique commonly used by geologists to judge fault hazard.

Unlike smaller quakes, the Landers quake did not confine itself to one segment of an individual fault. Starting on an unknown fault, it ruptured almost due northward for 20 kilometers and then turned northwest for another 50 kilometers, all told involving four different faults, says Sieh, who led a team of geologists in mapping the rupture where it reached the surface.

Seismologists find a similar story in the seismic waves measured around California and the world. In these wiggly records, researchers can detect two distinct parts of the Landers quake. The first batch of seismic waves – the smaller of the two – emanated from a north-south-directed fault. Then, about 10 seconds later, a second set of waves came from a fault farther to the north, oriented about 20° to the west of the first fault, says Hiroo Kanamori, director of the Caltech Seismological Laboratory.

The severity of that turn defies the kind of simple behavior that seismologists and geologists have seen in previous earthquakes, says Kanamori. According to traditional thinking, major breaks or bends in a fault tend to stop a rupture from spreading. Geologists often use such geographic obstacles to define discrete fault segments.

The concept of segmentation appeals to many researchers because it provides a framework for dissecting faults and gives hope for predicting fault behavior. In the best cases, some fault segments appear to generate so-called "characteristic" earthquakes – shocks of similar size that occur at roughly regular intervals. For instance, the Parkfield segment of the San Andreas has had magnitude 5.5 or 6 jolts about every 22 years for the last century (though the next one is overdue).

Even in cases where quakes do not recur so regularly, fault segmentation still appears useful. By measuring the length of a segment, geologists can estimate the maximum size of a future earthquake along that stretch.

Some geologists and engineers place great stock in magnitude estimates based on segmentation, says Jones. "We've been having an argument around here about the Sierra Madre fault," she says, referring to a fault that sparked a magnitude 5.8 jolt near Pasadena in June of last year. Because individual segments of the fault do not run more than 50 kilometers, some consulting geologists have suggested the fault would not produce any quakes greater than magnitude 6.5, Jones says.

Researchers have long recognized that large earthquakes can set several adjacent fault segments in motion. The great San Francisco earthquake of 1906 broke through three segments, as did the last great southern California earthquake, in 1857. But even in these cases, the segments were oriented in more or less the same direction. Geophysicists say they are particularly surprised by the sharp turn in the Landers rupture. "We haven't really seen this so distinctly before," says Kanamori.

If the Landers quake could rip from one fault to another and make major turns, it's a good bet others can as well, not only in California but around the world. That's bad news for proponents of segmentation. "The idea of segmentation that we've all been using somewhat simplistically is really being stretched at this point," Sieh says.

"The end result of this," says Jones, "is that you're going to see a lot less surety and a lot more waffle words when we are asked what's the biggest earthquake that a fault can produce."

At its heart, the problem comes down to a matter of time. A human generation spans just a tiny portion of a fault's lifetime, so seismologists have caught only a limited look at the wide range of earthquake behavior. "What it gets back to," says Jones, "is that we don't know very much." □

# *Enigmatic tremors erupt across West*

Like millions of other Californians, residents of Mammoth Lakes felt the earth shake on June 28, the day a magnitude 7.5 earthquake hit the southern Mojave Desert near the town of Landers. But Mammoth Lakes is a bit different from most other places rocked by that Sunday shock. Situated on the eastern edge of the Sierra Nevada, this town lies more than 400 kilometers away from the epicenter, too distant for slumbering people to feel the early morning Landers jolt.

Instead, Mammoth Lakes was having its own little earthquakes, which started within minutes of the major quake far to the south. At that same time, similar bursts of perceptible jolts and microquakes started at a dozen other sites in the western United States, including Mt. Shasta, southern Nevada, southern Utah, and even a little later at Yellowstone National Park, which lies a full 1,200 kilometers from the Landers epicenter.

"This is very unusual. I think bizarre is a good word to describe it," says geophysicist Paul Reasenberg, one of the many researchers at the U.S. Geological Survey (USGS) in Menlo Park, Calif., who are trying to make sense of the far-flung microquakes. Reasenberg says that before June 28, he wouldn't have believed it possible for a quake in southern California to trigger jolts at the other end of the state, let alone several states distant.

"This is one of those rare moments in science when your observational systems bring you something that you've never seen before," he says.

The phenomenon of distantly triggered quakes went unnoticed until now because large earthquakes had not occurred within a network of sensitive seismometers capable of detecting the microquakes.

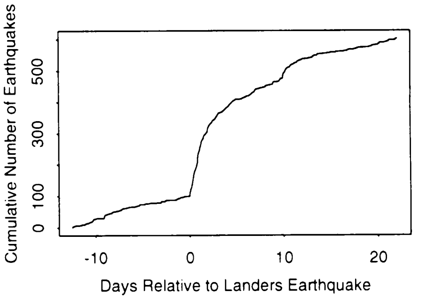
There have been hints of this kind of activity in the past. In 1906, 11 hours after the great San Francisco earthquake, a shock with an estimated magnitude of 6.2 occurred in the Imperial Valley, at the opposite end of the state.

Prior to the Landers event, investigators were wary about drawing connections between the San Francisco and Imperial Valley quakes. But recent events make a link seem more plausible. The post-Landers swarms led USGS seismologist William L. Ellsworth to take a close look at the seismicity records for 1906. In addition to the Imperial Valley shock, Ellsworth found nine earthquakes that occurred in California and Nevada within two days of the San Francisco quake. He calls these "candidates" for triggered earthquakes, cautioning that they may have been unrelated to the great quake.

Similarly, seismologists cannot be certain that the Landers quake triggered the seismic swarm at Yellowstone because this volcanic area has similar swarms quite often and the activity started almost two hours after the quake in southern California. In contrast, the swarms at Mammoth Lakes and several other areas were clearly triggered by the Landers shock because they started so soon after the major earthquake, Reasenberg says.

At present, geophysicists cannot explain how a major shock can trigger seismic unrest so far away. It is well known that tremors on one fault can raise the stress on nearby faults; indeed, the Landers earthquake triggered the magnitude 6.6 Big Bear earthquake on a separate fault. But such stress changes weaken with distance from the epicenter. Calculations made by Robert W. Simpson of the USGS indicate that at Mammoth Lakes, the static stress changes from the Landers quake would be weaker than the stresses induced daily by the tidal forces of the sun and moon.

Because static stresses appear too puny to spark distant quakes, most researchers are focusing on another type of stress change, a temporary one caused by seismic waves traveling through the Earth.




*Small quakes constantly occur near Mammoth Lakes, but the number of jolts surged on the day of the Landers quake.*

According to one theory, the seismic waves traveling under Mammoth Lakes may have shaken up a chamber of molten rock known to exist at a very shallow depth under this volcanic crater. Like shaking a soda bottle, the seismic waves would cause dissolved gases in the magma to come out of solution, forming bubbles in the magma. The expanding magma would then push on the crust, setting off small earthquakes, says USGS seismologist David Hill.

Hill believes the soda bottle model cannot explain all the seismic bursts, however, because many have occurred far from magma chambers. Another theory holds that the seismic waves somehow reduced the friction on faults, allowing ones already stressed to cause microquakes.

In any case, the mystery bursts have given geophysicists in northern California something to think about while their colleagues in the south study the nearby Landers quake. "I've been in this profession for close to 20 years," says Reasenberg, "and this has been the most exciting week I can remember." *— R. Monastersky*