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The 1992 Landers Earthquake Sequence

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At 4:58 a.m. (Pacific time) on June 28, 1992, a magnitude 7.4 earthquake occurred in the Mojave Desert of southern California. The epicenter was near the community of Landers, and the earthquake is referred to as the Landers earthquake (Figure 1). The earthquake was the largest to occur in the contiguous United States since the Kern County, California, earthquake (M_s = 7.7*) in 1952. Although the Landers earthquake was significantly larger than the 1989 Loma Prieta earthquake (M_s = 7.1, located in the Santa Cruz Mountains south of San Francisco), the damage was far less. Present estimates put the economic loss at $10 million, compared to $10 *billion* for the Loma Prieta earthquake. The Landers earthquake was widely felt in Arizona, and many residents of Tucson and Phoenix reported that "water had sloshed" out of their swimming pools. (See inset on swimming-pool seiches on page 3.) Many aspects of the Landers earthquake are very unusual and have heightened concerns that a major earthquake will occur on the southern San Andreas Fault in the near future.

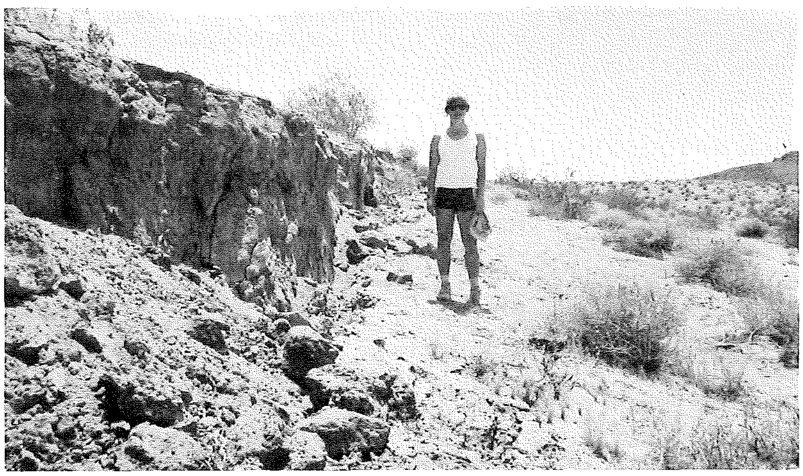

Figure 1. Fault scarp produced during Landers earthquake. Although the sense of motion on the fault is horizontal, large vertical scarps may form on sloping surfaces. Photo by David Wald.

The San Andreas Fault is a major expression of the North American-Pacific plate boundary, where the plates move past one another in a right-lateral sense† at a rate of 3.5 to 5.0 centimeters (1.4 to 2 inches) per year. North of Los Angeles, the San Andreas Fault makes a "big bend" and is oriented much more east-west than in northern California (Figure 2a). The trend of the San Andreas Fault near this bend is oblique to the relative motion of the two plates, resulting in their convergence. The Transverse Ranges (San Gabriel and San Bernardino Mountains) are a topographic expression of this convergence, as is the complexity of faults in southern California. South of latitude 34° N., the boundary between the North American and Pacific plates is distributed among at least three major faults: the San Andreas, San Jacinto, and Elsinore.

Another major fault in southern California is the Garlock Fault, which intersects the San Andreas Fault near latitude 35° N., longitude 119° W. The Garlock Fault is a left-lateral fault. The wedge-shaped region between the Garlock and San Andreas Faults is known as the Mojave Block (Figure 2b). The relative motion of the Garlock and San Andreas Faults requires that the Mojave Block undergo crustal extension. Numerous parallel faults cut the Mojave Block into "slats." These "slat faults" have right-lateral slip and accommodate the extension and rotation of the Mojave Block.

The Landers earthquake ruptured a 60-kilometer- (37-mile-) long segment of one of these Mojave Block faults. The sense of motion on the fault inferred from seismic waves was right-lateral strike-slip. At the epicenter (Figure 3), the surface displacement on the fault trace was approximately 3 meters (10 feet); near the northern end of the fault,

* Seismologists use four different magnitude scales to quantify the size of an earthquake. All of the scales are roughly equivalent and are based on the amplitudes of seismic waves corrected for the distance between the epicenter and recording station. M_s is **surface-wave magnitude**, the most commonly reported magnitude for large earthquakes, and is based on the amplitude of seismic waves that travel along the surface of the Earth. In comparison, **body-wave magnitude** (m_b) is based on the amplitude of seismic waves that travel through the interior of the Earth. M_L is **local magnitude**, the original magnitude scale developed by Charles Richter in the 1930's. M_w, or **moment magnitude**, is the most complete measure of earthquake size because it is directly based on the amount of energy released during an earthquake.

† Faults along boundaries where plates slide horizontally past each other are called **strike-slip faults** because the direction of movement (slip) is horizontal and parallel to the strike of the fault plane, i.e., the direction of its surface trace. **Right lateral** and **left lateral** refer to the two senses of movement on strike-slip faults. If you stand on either block along a right-lateral strike-slip fault and look across the fault, the block on the other side is displaced to the right. If you look across a left-lateral strike-slip fault, the block on the other side is displaced to the left.

ALSO IN THIS ISSUE

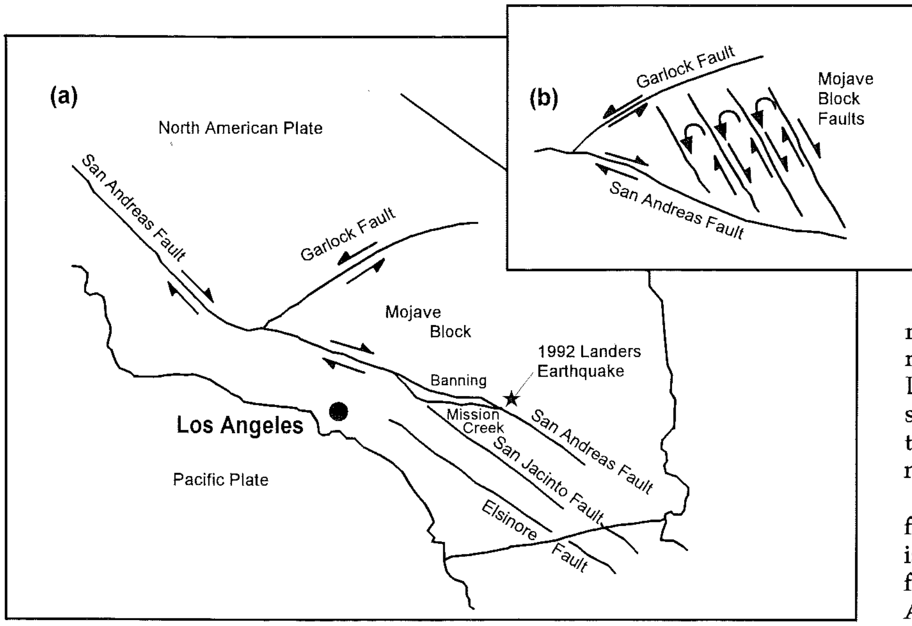

Figure 2. (a) Simplified fault map of southern California. The San Andreas Fault splits into two strands, the Banning and the Mission Creek near Cajon Pass. The 1992 Landers earthquake occurred north of the San Andreas Fault. (b) The Mojave Block is bounded on the north by the Garlock Fault and on the south by the San Andreas Fault. The Mojave Block is cut by a series of "slat" faults with right-lateral slip.

the displacement reached 6 meters (20 feet; Figures 1 and 4). The Landers earthquake **focal depth** (the depth at which the fault rupture began) was very shallow (2 to 3 kilometers or 1 to 2 miles), as were the focal depths of most of the aftershocks along the trend of the fault. These shallow depths are very unusual for strike-slip earthquakes in California, where most focal depths of large earthquakes have been 8 to 10 kilometers (5 to 6 miles). Although movement has occurred within the last 100,000 years along several mapped faults in the epicenter region, surface rupture from the Landers earthquake does not follow the trend of any single existing fault. The surface rupture is arcuate, trending from north-south near the epicenter to northwest at the northern extreme of the fault (Figure 3). Only at the northern end does the rupture merge with existing faults.

Approximately 3 hours after the Landers earthquake, a second large earthquake occurred 30 kilometers (18.5 miles) to the west. This earthquake (M_s = 6.5), known as the Big Bear earthquake because of its proximity to the mountain resort, ruptured a fault plane nearly perpendicular to the Landers Fault. The epicenter and aftershocks (Figure 3) outline a fault trend approximately 30 kilometers (18.5 miles) long. Although the Big Bear earthquake was much smaller than the Landers earthquake, it caused most of the damage during the earthquake sequence because (1) its epicenter was in a more populated region, and (2) many structures weakened by the Landers earthquake failed under the more moderate shaking of the Big Bear earthquake. The sense of slip along the Big Bear Fault was left-lateral. There was no surface rupture associated with this earthquake; the focal depth (9 kilometers or 5.5 miles) was much deeper than that of the Landers earthquake. The trend of the Big Bear Fault crosses numerous known faults, suggesting that the fault is a "new" feature.

As of this writing (August 17), 91 aftershocks with magnitudes larger than 4.0, including 13 with magnitudes larger than 5.0, have occurred in the Landers-Big Bear region. Although the aftershock activity is beginning to decrease, it is likely that several more earthquakes larger than magnitude 4.0 will occur in the next few months.

The relationship among existing mapped faults, the Landers Fault, and the Big Bear Fault is very complex. The Landers and Big Bear Faults form what is known as a **conjugate fault pair.** A simple theory of rock mechanics predicts that fractures on faults will form at an angle that is oblique to the direction of maximum compressive stress. For most rocks, this angle is approximately 60°. Two possible fracture planes can result, depending on whether the 60° angle is measured in a clockwise or counterclockwise direction. These two planes are a conjugate fault pair. This conjugate pairing of faults with opposite senses of motion is very rare in most parts of the world, although it may be the rule in the Mojave Block and along the southern San Andreas Fault. The 1979 Homestead Valley (m_b = 5.7) and 1987 Superstition Hills (M_s = 6.7) earthquakes showed such patterns. On July 5, 1992, a magnitude 5.1 earthquake occurred on the trend of the Big Bear Fault *east* of the Landers Fault. This suggests that the conjugate pattern continues across the Landers Fault. Special conditions may be required for conju-

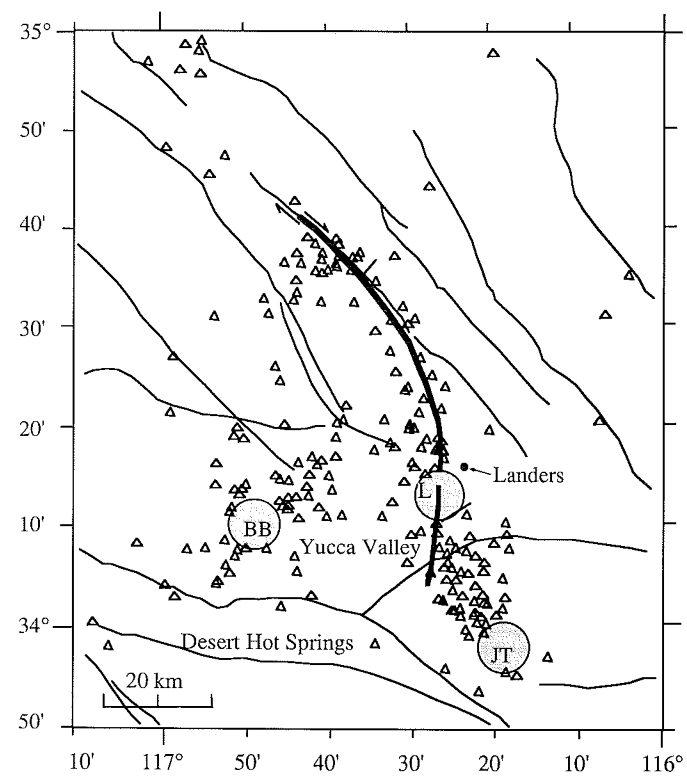

Figure 3. Location of Landers earthquake and significant aftershocks. Epicenters of three events are denoted by letters within large shaded circles: the Landers epicenter is labeled "L"; the Big Bear epicenter is labeled "BB"; and the Joshua Tree epicenter is labeled "JT." Epicenters of aftershocks are shown as triangles. Two trends are evident: the arcuate trace of the Landers Fault and the southwest-northeast trend of the Big Bear Fault. The thin lines signify Quaternary faults; the thick line is the trace of ground breakage associated with the Landers earthquake.

Swimming-Pool Seiches

One of the first things many Arizonans noticed on Sunday morning, June 28, was that the decks of their pools were wet. This is a common observation after large earthquakes have occurred in neighboring States: swimming pools lose water. The cause of this water loss is a wave known as a **seiche** (sāsh).

The ground shaking from a distant earthquake can make the surface of the water in a swimming pool uneven. Gravity causes water to rush from high parts of the surface to low parts. This produces a gravity water wave, which moves back and forth across the pool. If this wave is large enough, water will spill over the pool's edges. The size of a swimming-pool seiche depends on the geometry of the pool (its length, width, and depth) and on the location and size of the earthquake. Swimming-pool seiches can cause spillage of tens to hundreds of gallons of water.

Seiches have also been observed in lakes and partially closed bays after large earthquakes. The great Alaskan earthquake ($M_w = 9.2$) in 1964 caused a seiche in the Great Lakes in the north-central United States! *Seiche* is a French word coined by Swiss seismologist F.A. Forel, who studied the phenomenon in Lake Geneva and also developed the first earthquake-intensity scale.

gate pairing, such as a large crustal region that is strained everywhere to a point near failure.

The Landers earthquake was preceded by a magnitude 6.1 foreshock on April 23, 1992. Named the Joshua Tree earthquake (Figure 3), it was felt in Las Vegas and Phoenix, although damage was relatively minor. The Joshua Tree aftershock sequence was extremely energetic and protracted. A typical aftershock sequence from a magnitude 6 earthquake would be only a few weeks long, and only four or five events would be larger than magnitude 4.0. Twelve aftershocks larger than magnitude 4.0 followed the Joshua Tree earthquake, however, and aftershocks continued up to the time of the Landers earthquake, more than 9 weeks later. Many of the Joshua Tree aftershocks were very high-stress **drop earthquakes,** meaning that the aftershock faulting process involved more slip than is typical. In hindsight, it is obvious that the Joshua Tree earthquake was a precursor to the Landers earthquake because the Joshua Tree fault zone merges with the southern end of the Landers fault zone. Perhaps the aftershock activity could have been used to issue a warning for the Landers earthquake.

Some of the most interesting phenomena after the Landers earthquake were observed hundreds of kilometers (or miles) from the epicenter. Within minutes after the Landers earthquake, hundreds of small earthquakes occurred near the Mammoth Lakes in north-central California and near Mount Shasta in northern California. Both of these areas are volcanic regions. In addition to the earthquake activity, hydrological phenomena occurred in both regions, including temperature rises in hot springs and increased geyser activity. Conventional theory predicts that the strain change due to the Landers earthquake should be infinitesimal only 100 kilometers (62 miles) away from the epicenter. This unexpected far-flung effect will cause seismologists to reevaluate the correlation of earthquakes. For example, on July 5, 1992, a magnitude 5.5 earthquake occurred on the Nevada-California border south of the Nevada Test Site. Was this earthquake triggered by the Landers sequence? Before June 28, the stock answer would have been "No," but now the answer is "We don't know."

Seismologists are concerned that the Landers earthquake sequence has significantly increased the potential for a major earthquake on the southern San Andreas Fault. The wedge of material defined by the Big Bear Fault, Landers Fault, and Mission Creek strand of the San Andreas Fault moved north on June 28 as a consequence of left-lateral slip on the Big Bear Fault and right-lateral slip on the Landers Fault. This implies that the **normal (perpendicular) stress** *across* the San Andreas Fault decreased. Faults slip in earthquakes when the **shear (tangential) stress** *along* the fault exceeds the frictional resistance of the fault surface. This frictional resistance is directly proportional to the normal stress across the fault. If one assumes that normal stress inhibits fault slip, then the stress that would restrain movement has been reduced along an 80-kilometer (50-mile) section of the San Andreas Fault. The southern 200 kilometers (124 miles) of the San Andreas Fault, from Cajon Pass in the north to the Salton Sea in the south, has not generated a great earthquake ($M \geq 7.0$) for at least 300 years, although the fault was very active between A.D. 1000 and 1700. Sieh (1986) reported that at least 21 meters (69 feet) of right-lateral slip occurred during four large ($M \geq 7.0$) earthquakes within this 700-year interval. His data are consistent with an earthquake-recurrence interval of about 200 to 300 years; it has been about 300 years since the last major earthquake. The conditions appear to be favorable for a magnitude 7.5+ earthquake on the southern San Andreas Fault. Based on the lapse time between the Joshua Tree earthquake and the Landers earthquake (2 months), a window of at least 6 months for "triggering" a large earthquake along the San Andreas Fault is scientifically reasonable.

The 1992 Landers earthquake sequence is causing seismologists to rethink a significant portion of the conventional wisdom about earthquake behavior. For example, why did the Landers earthquake form a new fault instead of causing slip on a preexisting fault? Conventional wisdom would say that much more stress is required to break new rock than to cause slip on an existing zone of weakness. During this century, all

Figure 4. Right-lateral fault 28 miles northwest of Landers. The fault crosses a dirt road and offsets the tracks and line of creosote bushes by 12.8 feet. Photo by David Wald.

strike-slip earthquakes that have occurred in the western United States can be attributed to preexisting faults — all except those in the Landers sequence. Also, why did 3 hours elapse between the Landers and Big Bear earthquakes? Conventional wisdom would say that within seconds after the Landers earthquake, the stress effects should have stabilized in the Big Bear region. Similarly, why didn't the Landers sequence immediately trigger a major earthquake on the San Andreas Fault? Detailed studies of the Landers earthquake sequence will undoubtedly result in a much-improved understanding of fault dynamics and will ultimately result in better predictions of earthquake hazards.

Reference

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Dr. Terry C. Wallace, Jr., seismologist and professor of geosciences at the University of Arizona, received the Macelwane Award from the American Geophysical Union. This annual award is presented to scientists aged 36 or younger who are considered to be the best in their field and who have made significant contributions to the area of geophysics. Wallace received B.S. degrees in geophysics and mathematics and M.S. and Ph.D. degrees in geophysics. He has researched earthquakes in the western United States, China, Africa, South America, the Indian Ocean, and the Mediterranean. Wallace has written several articles for *Arizona Geology* on earthquakes in southern Arizona, northern Sonora, and California.

Southern Arizona Seismic Observatory

The Southern Arizona Seismic Observatory (SASO) is an organized research group in the Department of Geosciences at the University of Arizona. SASO scientists conduct research on different aspects of seismology, fault mechanics, and geodynamics. SASO operates the prototype IRIS/NSN seismic station TAZ in the Santa Catalina Mountains near Tucson. One of the most advanced stations, TAZ is part of the Global Seismic Network (GSN) and the National Seismic Network (NSN). TAZ uses state-of-the-art, very broadband sensors, which can detect ground vibrations with frequencies from .0001 to 20 Hz. The station also uses a 24-bit digitizer to give the signals very wide dynamic range (18 orders of magnitude). The seismometers, digitizer, and data-acquisition module are located at the remote site. The data are transferred to the data-processing center on the University of Arizona campus via a dedicated phone line. At this center, the seismic signals are formatted for various uses, and the data are broadcast in real time via a satellite link to the National Earthquake Information Center in Golden, Colorado. This satellite link is also used to download seismic signals from other NSN stations to SASO.

One of SASO's missions is to disseminate earthquake information rapidly to government agencies, private industry, and the public. SASO is connected via a network link with seismic centers at the U.S. Geological Survey and California Institute of Technology. In the event of a significant earthquake, SASO will produce a scientific update within 12 hours. SASO will also produce a monthly bulletin of earthquakes that occur in or affect Arizona. For more information on SASO and subscriptions to this bulletin, write to or call Terry C. Wallace, SASO, Dept. of Geosciences, Gould-Simpson, Bldg. 77, University of Arizona, Tucson, AZ 85721; (602) 621-4849.

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seismic policy, education, and awareness for which there is no assigned responsibility within the State. The local equivalent of the Advisory Committee for the National Earthquake Hazard Reduction Program, ACES will coordinate government and private-sector seismic-safety practices, evaluate earthquake programs, and monitor compliance with building laws. Short-range plans include developing a charter, defining the organization's structure, and gaining official recognition through an Executive Order. ACES members are also developing a long-term strategy to establish this body as an independent source of credible, technical and nontechnical, seismic information and advice to the public, the private sector, and the executive and legislative branches of State government.

Reference

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