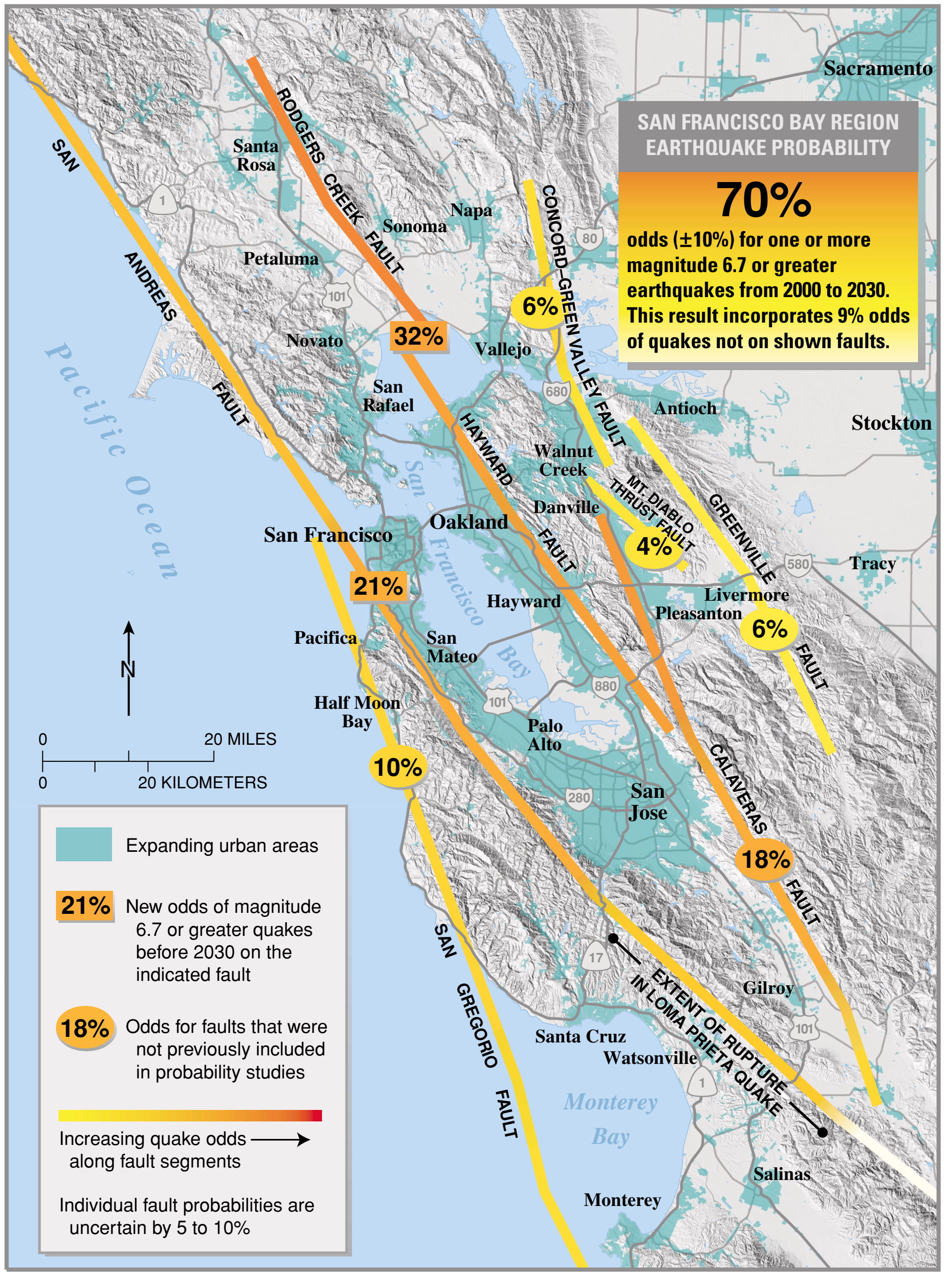
USGS
science for a changing world

Major Quake Likely to Strike Between 2000 and 2030

On the basis of research conducted since the 1989 Loma Prieta earthquake, U.S. Geological Survey (USGS) and other scientists conclude that there is a 70% probability of at least one magnitude 6.7 or greater quake, capable of causing widespread damage, striking the San Francisco Bay region before 2030. Major quakes may occur in any part of this rapidly growing region. This emphasizes the urgency for all communities in the Bay region to continue preparing for earthquakes.



The threat of earthquakes extends across the entire San Francisco Bay region, and a major quake is likely before 2030. Knowing this will help people make informed decisions as they continue to prepare for future quakes.

Just before dawn, residents of a bayside urban area, thought to be well prepared for earthquakes, were jolted from their beds by a magnitude 6.9 quake. This 1995 temblor killed more than 6,000 people and caused $100 billion in damage. The quake struck Kobe, Japan, but similar losses could have occurred in the San Francisco Bay region in 1989 had the magnitude 6.9 Loma Prieta earthquake been centered in an urbanized area.

Damaging earthquakes are inevitable in the Bay region, but taking actions based on the odds of future quakes will help save lives and protect property. Following the Loma Prieta quake, the U.S. Geological Survey's (USGS) Working Group on California Earthquake Probabilities reassessed the likelihood of large quakes striking the Bay region and issued a report in 1990.

Since then, scientists have gained new insights into Bay region earthquakes, providing a better basis for determining quake odds. In 1997, the USGS working group, now known as WG99, was expanded to include more than 100 scientists from Federal and California State governments, consulting firms, industry, and universities.

Earthquake probabilities are based on balancing the continual motions of the plates that make up the Earth's outer shell with the slip on faults, which occurs primarily during earthquakes. To determine Bay region earthquake probabilities, WG99 gathered new data, developed analytical tools, and debated a wide variety of interpretations about how future temblors may occur (*see inside pages for further details*).

WG99 determined that there is a 70% chance (±10%) of at least one magnitude 6.7 or greater earthquake striking the San Francisco Bay region between 2000 and 2030. This result is the most important outcome of WG99's work, because any major quake can cause damage throughout the region. This was **[continued on back page]**

CALCULATING THE EARTHQUAKE ODDS

In 1997, the U.S. Geological Survey's (USGS) Working Group on California Earthquake Probabilities was expanded to include more than 100 geologists, seismologists, geophysicists, and mathematicians. This group, known as WG99, calculated new quake odds for the San Francisco Bay region based on insights gained since the 1989 Loma Prieta earthquake. WG99 concluded that there is a 70% probability (±10%) of at least one magnitude 6.7 or greater quake, capable of causing widespread damage, striking the region before 2030. The process used to determine these odds is described below.

Balancing plate motions and earthquakes

Quake probabilities for the San Francisco Bay region are derived by balancing two processes—(1) the motions of the plates that make up the Earth's outer shell and (2) the slip on faults, which occurs primarily during earthquakes. The continual northwestward motion of the Pacific Plate past the North American Plate loads strain onto the network of active faults that slice through the region. Earthquakes sporadically release and redistribute this strain. WG99 combined geology, physics, and statistics to balance these processes and calculate quake odds.

One side of the balance is the rate at which plate motions load strain onto faults. Development of the Global Positioning System (GPS) has allowed geophysicists to make accurate measurements of how the current plate motions—totaling 1.5 inches per year across the entire region—distributes strain onto individual faults. Geologic studies also contribute to this understanding by documenting long-term fault motions, which must match the strain-loading rate. For example, on the San Gregorio Fault near Moss Beach, a buried stream channel has been offset about 1,000 feet over the past 80,000 years. This indicates that the strain rate there is about one-sixth of an inch per year, a small fraction of the total regional plate motions. Offshore studies reveal other active strands of the San Gregorio Fault that account for additional strain.

The other side of the balance is the slip on faults, which over time must account for the strain built up by the plate motions. Slip on faults (movement of one side of a fault relative to the other) can occur either during earthquakes or during slow, aseismic (without earthquakes) creep. For example, creep on the Hayward Fault is slowly offsetting street curbs, even in the absence of large quakes. Where aseismic creep occurs, it affects the balance between plate motions and earthquakes by relieving strain, which can either change the likelihood or lower the magnitude of future quakes. Nevertheless, most slip on faults occurs during earthquakes—the larger the quake, the greater the slip.

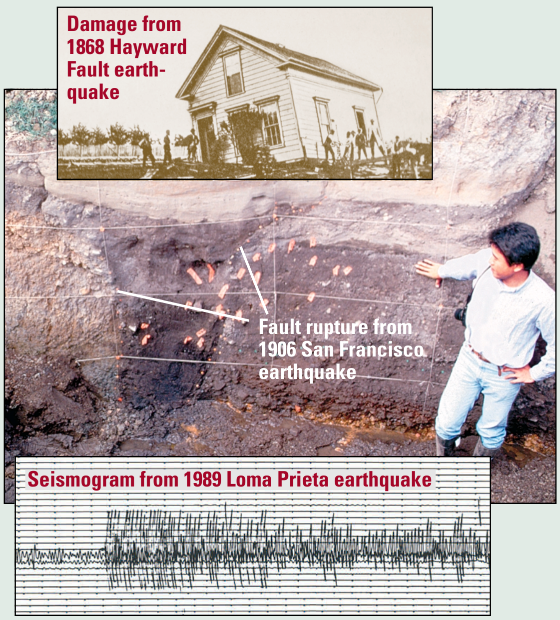
Earthquake history

Knowledge of past earthquakes indicates what sizes of quakes to expect in the future. The most accurate locations and magnitudes exist for quakes recorded on seismographs, which came into widespread use about 1900. However, this record is too short to understand the pattern of earthquakes over geologic time. Historical accounts of damage help identify and locate quakes that occurred before there were adequate seismographic records (seismograms), but such accounts are fragmentary in northern California before 1850. Scientists reanalyzed seismograms and historical accounts as part of WG99's efforts.

To go back even further in time, geologists dig trenches across faults to uncover earthquake ruptures that once reached the surface but now are buried. Many new trenches across Bay region faults expose the ancient earthquake history. For example, a trench in El Cerrito revealed evidence of four to seven large quakes on the Hayward Fault during the past 2,200 years.

Understanding faults

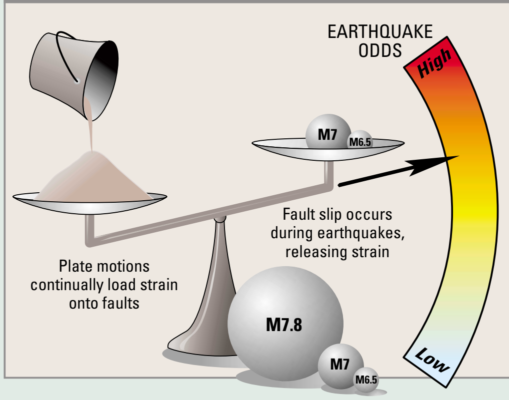
Data from trenches, historical accounts, and seismograms provide incomplete information about quakes in the San Francisco Bay region. Supplementing this with up-to-date knowledge about how faults work allows scientists to make better projections of the expected sizes of future earthquakes.



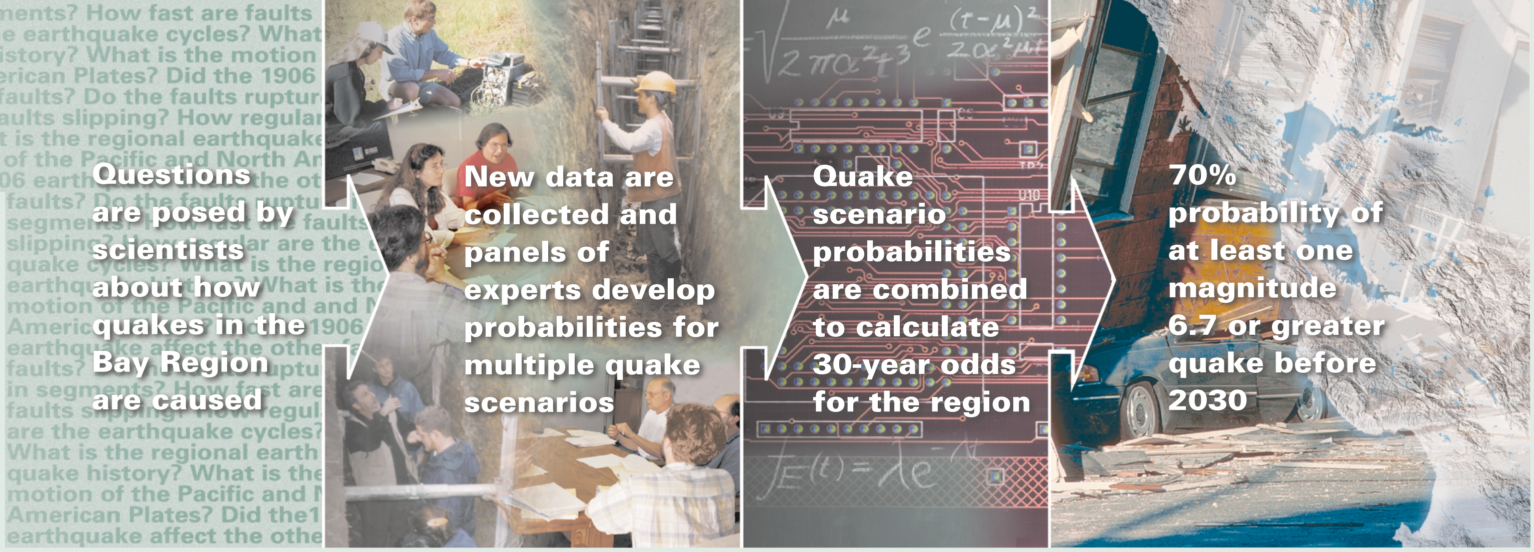
Knowledge of past earthquakes is essential for estimating the odds of future temblors. This knowledge comes from (top to bottom) historical damage accounts, fault ruptures exposed in trenches, and seismographic records.

Many Earth scientists believe that faults are composed of segments that may rupture individually or in groups of adjacent segments during an earthquake, and WG99 used this concept. Larger quakes rupture greater fault lengths and produce more slip. For example, the magnitude 7.8 San Francisco earthquake of 1906 ruptured 300 miles of the San Andreas Fault and produced as much as 30 feet of slip, whereas the magnitude 6.9 Loma Prieta quake in 1989 ruptured only 25 miles of fault and produced only about 6 feet of slip. If scientists can

THE "EARTHQUAKE PROBABILITY BALANCE"



Quake probabilities are derived by balancing two processes—(1) the continual motions of the plates that make up the Earth's outer shell (represented by pouring sand onto the left tray) and (2) the slip on faults, which occurs primarily during earthquakes (equivalent to adding balls to the right tray). The slip on faults over time must balance the strain built up by the plate motions. The total amount of slip during an earthquake, shown here by the proportional volumes of the spheres, depends on its magnitude (M). The larger the quake, the more strain released.



identify the lengths of fault segments that may fail together in an earthquake, they can estimate the magnitudes and amounts of slip for possible future quakes.

Earth scientists identify fault segments by studying bends, intersections, and gaps in faults, past earthquakes, and major changes in rock types along faults. One example of how past earthquakes define segments is the 1868 magnitude 6.9 quake on the Hayward Fault. This quake ruptured only the southern part of the fault, defining that part as a segment that can rupture separately. However, WG99 concluded that an even-larger earthquake might rupture the entire Hayward-Rodgers Creek Fault.

Finding new faults

In addition to identifying fault segments, WG99 looked for previously unknown faults. Most faults in the San Francisco Bay region have "strike-slip" motion, in which the two sides of the fault slip horizontally past each other. In contrast, ramp-like "thrust" faults have vertical motion and often do not reach the Earth's surface, making them difficult to find. The importance of locating these hidden faults was underscored by the devastating 1994 Northridge earthquake in southern California, which occurred on a previously unknown thrust fault.

Of the known thrust faults in the Bay region, only the Mount Diablo Thrust Fault has a high enough slip rate to be included in WG99's calculations. To account for the small percentage of large earthquakes that occur on minor or unknown faults (both strike slip and thrust), WG99 estimated probabilities for such quakes on the basis of the rate of similar quakes in the historical record.

A new method for determining quake odds

Scientists can best determine earthquake probabilities for a fault once they know when it last ruptured, the sizes of possible quakes, and the rates of plate motions. For example, if plate motions are loading a fault at 1 inch per year, the fault will accumulate 100 inches of strain in 100 years. If each earthquake on that fault releases 100 inches of slip and there is no aseismic creep, then one quake can be expected every 100 years. If the occurrence of that earthquake is equally likely at any time, the odds of it striking would be 1% in any given year. However, many earthquake experts believe that once a fault slips, plate motions must load strain back onto that fault before the next quake can occur. If quakes occurred with perfect regularity, then in this example they would occur exactly 100 years apart, and the odds of a quake would be 0% for the first 99 years and 100% for the final year.

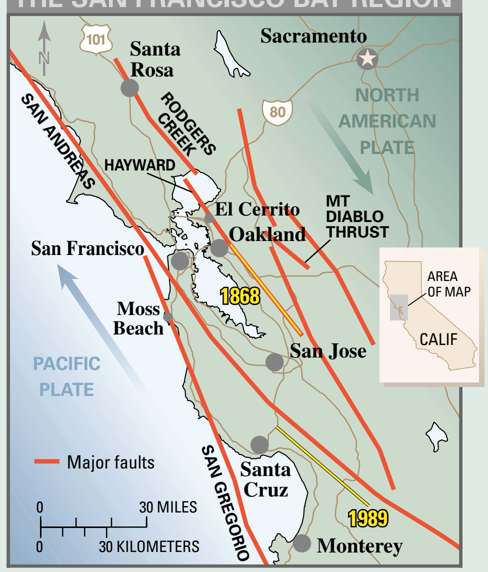
Earthquakes, however, are not that predictable. WG99 therefore developed a new set of models that use both physics and statistics. In these models, quakes are caused by a combination of constant plate motions and a random process that accounts for variations in earthquake sizes and occurrence. These models closely mimic the occurrence of quakes around the world.

Because every earthquake changes strain on nearby faults, another important element in the WG99 method is the inclusion of interactions between faults in the San Francisco Bay region. For example, the rate of large quakes in the region was high in the late 1800's but abruptly dropped after the 1906 San Francisco earthquake. Scientists believe that this rate dropped because the San Andreas Fault slipped so much over such a great length in 1906 that the strain was reduced on most faults throughout the Bay region. Because plate motions are continuous, strain has been slowly building up again, and strong earthquakes began to occur again in the 1980's. However, the level of seismic activity has not yet reached that of the late 1800's (see diagram on back page).

The WG99 method for determining earthquake probabilities involves making many decisions, such as defining fault segments and choosing among alternative statistical models. Every such decision is uncertain, but WG99 members assigned weights to the various choices so that all of them were included in their overall calculations.

This process helps ensure that the WG99 probabilities are reliable estimates of the earthquake threat faced by the San Francisco Bay region between 2000 and 2030. The WG99 method will also allow the USGS to update these probabilities as new insights are gained.❖

FAULTS AND PLATE MOTIONS IN THE SAN FRANCISCO BAY REGION



The San Francisco Bay region lies on the boundary zone between two of the tectonic plates that make up the Earth's outer shell. The relentless motion of these plates builds up strain that will eventually be released in earthquakes on the region's many faults. The lengths of fault that slipped in the 1868 Hayward and 1989 Loma Prieta magnitude 6.9 earthquakes are shown in yellow.

[continued from front page]

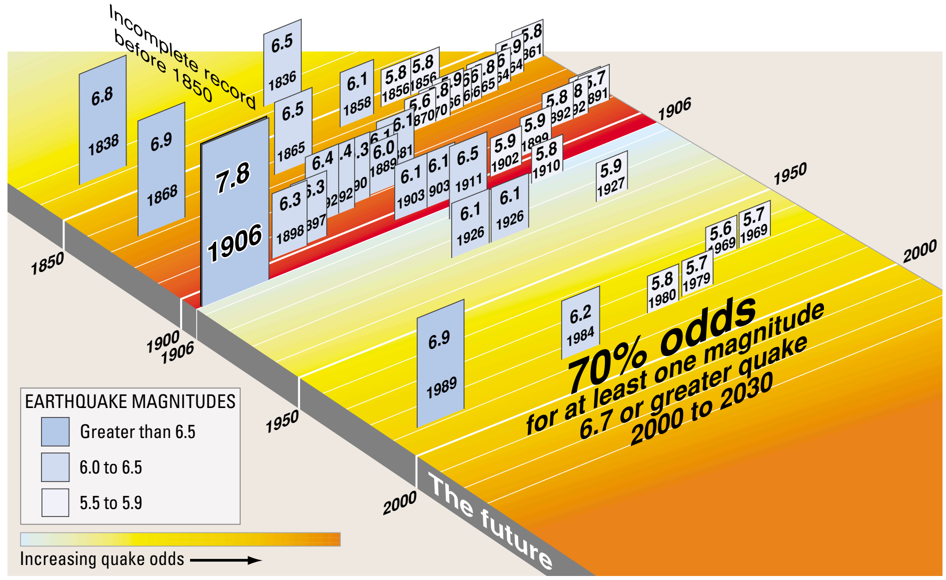
dramatically demonstrated when the 1989 Loma Prieta earthquake caused severe damage in Oakland and San Francisco, more than 50 miles from the fault rupture. Although earthquakes can inflict damage at a considerable distance, shaking will be very intense near the fault rupture. Therefore, temblors located in urbanized areas of the region have the potential to cause much more damage than the 1989 quake.

In the Bay region's rapidly growing eastern valleys, four faults slice through Contra Costa, Alameda, Solano, Santa Clara, San Benito, and Napa Counties. WG99 calculated the odds of major quakes on these faults for the first time. They determined that there is a 30% chance of one or more magnitude 6.7 or greater quakes occurring somewhere on the Calaveras, Concord-Green Valley, Mount Diablo Thrust, and Greenville Faults before 2030.

Residents living near the Pacific coast in burgeoning San Mateo, Santa Cruz, and Monterey Counties are sandwiched between the San Andreas and San Gregorio Faults. New data have allowed WG99 to calculate the first earthquake probabilities for the San Gregorio Fault and to better estimate probabilities for the San Andreas Fault. Combined, these two faults have a 25% chance of producing one or more magnitude 6.7 or greater quakes in these coastal areas before 2030.

When the 1990 USGS probability report was released, earthquake odds could be estimated only for the San Andreas Fault and the Hayward-Rodgers Creek Fault, although the danger posed by other faults was recognized. WG99 found that, of all the faults in the Bay region, these two and the Calaveras pose the greatest threat, because they have high quake odds and run through the region's urban core.

There are important differences between the 1990 and WG99 studies. WG99 analyzed five additional faults, which would be expected to increase the estimated regional probability of major quakes. This expected increase was largely compensated for, however, by two effects not included in the 1990 report: (1) slip on faults in the absence of earthquakes and (2) the effect of the 1906 earthquake in reducing quake activity throughout the region.



The rate of large earthquakes in the San Francisco Bay region abruptly dropped after the Great 1906 Earthquake. The San Andreas Fault slipped so much over such a great length in that quake that the strain was reduced on most faults throughout the region. Strain has been slowly building up again. However, the level of seismic activity has not yet reached that of the late 1800's.

Additionally, the 1990 study considered only earthquakes of about magnitude 7 in determining there was a 67% chance of major quakes in the Bay region between 1990 and 2020. WG99 decided to focus on earthquakes of magnitude 6.7 and greater in their calculations, because the 1994 Northridge quake in southern California was only magnitude 6.7 yet killed 57 people and caused more than $20 billion in damage.

Magnitude 6.7 or greater quakes can cause damage throughout the Bay region, but even smaller quakes could be serious if centered in an urbanized area. WG99 found an 80% chance of one or more magnitude 6 to 6.6 quakes occurring in the Bay region before 2030.

WG99's conclusions from their 2-year effort are to appear in USGS Circular 1189, "Earthquake Probabilities in the San Francisco Bay Region: 2000 to 2030." Their finding that a major temblor is more likely than not emphasizes the ongoing need for the Bay region to prepare for earthquakes.

Large earthquakes in the San Francisco Bay region can produce sudden and tremendous loss of life and property, threatening the social and economic fabric of this region. Although quakes cannot be prevented, the damage they do can be greatly reduced through prudent planning and preparedness. Much preparation has already been done, but because a large quake is likely and could happen at any moment, further preparations should not be delayed. WG99's results will help business, government, and the public make informed decisions as they continue their preparations.

The work of USGS and other scientists in evaluating earthquake probabilities for the San Francisco Bay region is an ongoing part of the National Earthquake Hazard Reduction Program's efforts. These efforts help to safeguard lives and property from the earthquakes that will inevitably strike in northern California and elsewhere in the United States.

SIMPLE STEPS TO EARTHQUAKE PREPAREDNESS

Before the next quake, learn:

- **What to do during a quake,**
- **What supplies to have on hand, and**
- **How to make sure your home, office, and schools are safe.**

Some good places to get preparedness information are the front of telephone directories, libraries, the Red Cross, the California Governor's Office of Emergency Services (510-286-0873), and *http://quake.usgs.gov*.

Andrew J. Michael, Stephanie L. Ross, David P. Schwartz, James W. Hendley II, and Peter H. Stauffer

Graphic design by
Susan Mayfield, Sara Boore, and Michael F. Diggles

COOPERATING ORGANIZATIONS
Association of Bay Area Governments
California Division of Mines and Geology
California Governor's Office of Emergency Services
Federal Emergency Management Agency
Lawrence Livermore National Laboratory
Geomatrix Consultants Inc.
Pacific Gas and Electric Company
University of California at Berkeley
William Lettis & Associates
Many other institutions, organizations, and firms

For more information contact:
Earthquake Information Hotline (650) 329-4085
U.S. Geological Survey, Mail Stop 977
345 Middlefield Road, Menlo Park, CA 94025
http://quake.usgs.gov/
See also *Progress Toward a Safer Future Since the 1989 Loma Prieta Earthquake* (USGS Fact Sheet 151-99)