Understanding Seismic Hazards 2

Earthquakes remind us that the earth is continually changing, sometimes with disastrous consequences for its inhabitants and for the relatively fragile structures built atop its outermost layer. Our understanding of the seismic hazard (i.e., the potential for earthquakes and related effects) has improved significantly in the last two decades, largely through research supported by the National Earthquake Hazards Reduction Program (NEHRP). This improved knowledge of the seismic hazard can in turn be applied to better estimation of the potential impact on specific communities. For example, earthquake-related research and development (R&D) to date has yielded detailed information on historical and estimated future ground motions that earthquake engineers now use for research, design, and building code development.

Federal support for earthquake-related R&D in the earth sciences is concentrated in programs directed by both the National Science Foundation and the U.S. Geological Survey (USGS) under the aegis of NEHRP; other federal agencies conduct related research as well (see appendix B). Since focused efforts began, there have been many achievements in earth sciences. However, the complexity of the task of understanding earthquake phenomena means that significant uncertainties remain about the timing and location of future damaging earthquakes and the exact nature of their effects.

This chapter reviews the current knowledge of earthquake phenomena and of seismic hazards across the United States. It then outlines the role of basic and applied earth science R&D in meeting information needs for the nation's earthquake loss mitigation program, and provides examples of research efforts needed to address knowledge gaps.

EARTHQUAKES

An "earthquake" technically refers to trembling or strong ground shaking caused by the passage of seismic waves through the earth's rocky interior. These waves arise from phenomena as varied as explosions,[1] volcanic eruptions, or quarry blasts, but the source most commonly associated with the term is the fracturing, or *faulting,* of rocks deep underground through the action of powerful geologic forces.

Seismic waves radiate away from a rupturing fault in the same way that ripples in a pond spread outward from a splashing pebble. These waves die away with distance from the initial source, so that very distant or very deep earthquakes are of relatively little concern. Like pond ripples, the waves can bounce and bend around obstacles to produce intricate patterns. Because the structure of the earth is far more complicated than the surface of a pond, what happens when seismic waves reach the earth's surface can be exceedingly complex.

Efforts to assess risks to U.S. communities posed by future earthquakes rest on the ability to estimate where and when earthquakes will occur and to quantify, where possible, what will happen when earthquake-generated seismic waves hit the earth's surface. (Figure 2-1 illustrates seismicity that has occurred in the United States.) Specific questions addressed by current earth science research include:

- What causes a particular fault to rupture?
- How do seismic waves propagate through the earth?
- How do seismic waves and local geology interact to produce strong ground motions[2] or damage to the earth's surface?

Two distinct methods of evaluating the severity of an earthquake are: 1) calculating its *magnitude,* and 2) estimating its *intensity.* The magnitude of an earthquake is related to the amount of seismic energy released at the quake's source; it is based on the amplitude of the seismic waves recorded on seismographs. Earthquake magnitude calculations also take into account the effects of distance between the recording instrument and the source of the waves, and the type of instrument itself.[3]

The magnitude scale most widely used for many years is the Richter magnitude scale, introduced in 1935 by Charles Richter and Beno Gutenberg. A strong earthquake, for example, would have a Richter magnitude (M) of 6.0 to 7.0, while a great earthquake such as the 1906 earthquake beneath San Francisco would measure above M8. Although it is open-ended, the Richter scale does not accurately measure large earthquakes on faults with a great rupture length.[4] To better quantify the severity of great quakes, scientists have developed the moment magnitude scale. The moment magnitude (Mw) measures the total seismic energy released, which is a function of rock rigidity in the fault, the area of rupture on the fault plane, and the amount of slip. These scales are compared in table 2-1.

In contrast to magnitude, an earthquake's *intensity* is a highly subjective measure. For many years the Modified Mercalli Intensity (MMI) scale, developed in 1931, has been used to describe the relative strength of ground shaking experienced at a particular location. Seismologists assign intensity using the 12-increment scale that reflects the effects of shaking on people, damage to the built environment, and changes in the natu-

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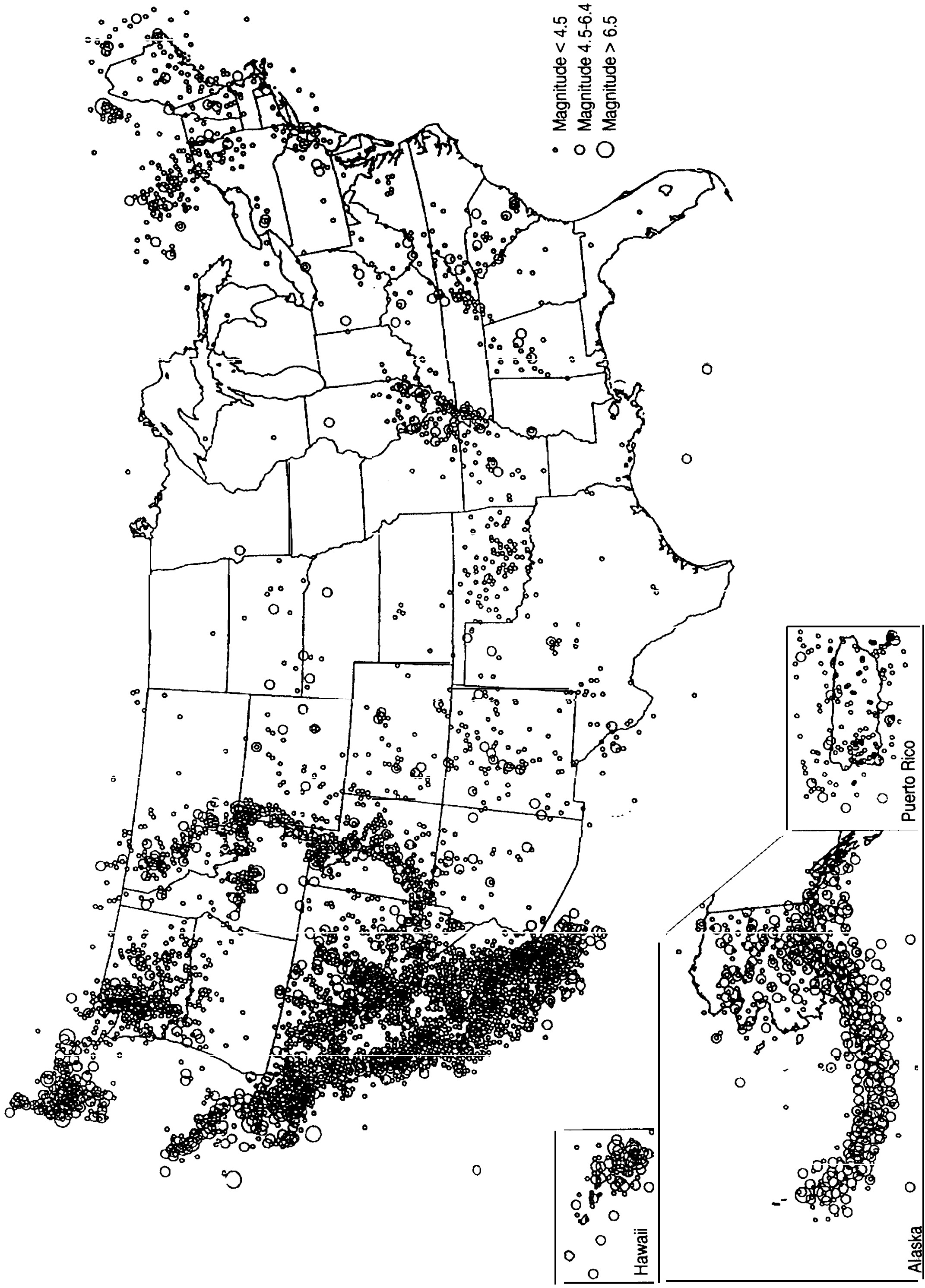
[1] Nuclear explosions, for example, generate seismic waves that can be detected at great distances by earthquake-monitoring networks.

[2] Strong motions are energetic ground displacements that cause damage to buildings and other structures.

[3] U.S. Geological Survey, "The Severity of an Earthquake," brochure, 1990. This report adopts the classification for quakes of different strengths as follows (M=magnitude): moderate, M5-6; strong, M6-7; major, M7-8; and great, M>8.

[4] Much of the energy of a large earthquake is transmitted via long-wavelength seismic waves, the frequency of which is too low to factor into calculations of earthquake magnitude.



SOURCE: U.S. Geological Survey, National Earthquake Information Center.

TABLE 2-1: Comparison of Richter and Moment Magnitudes for Selected Quakes

Earthquake	Richter magnitude	Moment magnitude
Chile, 1960	8.3	9.5
Alaska, 1964	8.4	9.2
New Madrid, Missouri, 1812	8.7	8.1
Mexico, 1985	8.1	81
San Francisco, California, 1906	8.3	77
Loma Prieta, California, 1989	7.1	7.0
Kobe, Japan, 1995	6.8	69
San Fernando, California, 1971	6.4	6.7
Northridge, California, 1994	6.4	6.7

SOURCE: Rick Gore, "Living with California's Faults," *National Geographic, vol.* 187, No. *4*, April 1995, p 10

ral environments Table 2-2 provides an abbreviated description of the MMI scale.

Continuing research has illuminated both the basic setting for earthquakes and their hazardous effects. These two topics set the stage for understanding the seismic hazards that exist in different areas of the country.

Geologic Setting for Earthquakes

The overall framework that guides the discussion of earthquake occurrence is the theory of plate tectonics, a large-scale picture of the earth's basic workings originally set forth in the 1960s and 1970s.[6] In this conceptual framework, the rocks making up the outer layers of the earth are broken into a patchwork of ever-shifting tectonic plates (see figure 2-2). Some of these plates are enormous—the rocks underlying much of the Pacific Ocean, for example, lie on a single 10,000-km-wide Pacific Plate—whereas others may span only a few hundred kilometers. What distinguishes a plate, however, is that it moves as a cohesive body across the surface of the earth.[7] As a plate moves, it grinds or knocks against its neighbors; this plate-to-plate interaction produces the majority of the world's earthquakes.

With a few significant exceptions, identifying the most likely breeding ground for darnaging earthquakes is thus synonymous with finding the boundaries of tectonic plates. The two types of plate boundaries associated with damaging earthquakes in the United States are subduction zones and strike-slip faults. In addition, there are intraplate earthquakes, whose origins are less well understood[8] (see box 2-l).

Earthquake Effects at the Earth's Surface

Besides knowing where and when earthquakes might occur, those interested in reducing earth-

5 "Quake Intensity," *Earthquakes and Volcanoes,* vol. 24, No. 1, 1993, p. 42.

15 It should be noted that many of the data that supported the theory's development were derived from pre-NEHRPefforts (e.g., Department of Defense mapping of seafloors, and global seismic monitoring aimed at detecting nuclear testing in the former Soviet Union).

7 This motion is slow—usually on the order of a few centimeters or less per year. Over millions of years, however, it can carry continents from the equator to the poles, rip landmasses apart, or assemble disconnected land fragments into continents.

8 Intraplate quakes, which can strike deep within a plate's interior, are relatively rare. There are also earthquakes associated with mountain-building and active continental deformation far inland from plate boundaries. One theory is that such activity in western states reflects the presence of a diffuse plate boundary stretching from the Pacific coast to the front ranges of Utah, in which case earthquakes in the Intermountain West are not "intraplate" quakes at all. This report adopts the convention that the North American Plate ends near the Pacific coast and that earthquakes in the Intermountain West are intraplate events.

TABLE 2-2: Modified Mercalli Intensity Scale and Corresponding Effects

MMI	Description
I	Not felt except by a very few under especially favorable circumstances.
II	Felt only by a few persons at rest, especially on upper floors of buildings.
III	Felt quite noticeably indoors, especially on upper floors of buildings.
IV	During the day, felt indoors by many, outdoors by few. At night, some awakened.
V	Felt by nearly everyone; many awakened. Some dishes, windows broken; a few instances of cracked plaster; unstable objects overturned
VI	Felt by all; many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight.
VII	Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures. Some chimneys broken.
VIII	Damage slight in specially designed structures; considerable in ordinary substantial buildings, with partial collapse; great in poorly built structures. Chimneys, factory stacks, columns, monuments, and walls fall.
IX	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb, damage great in substantial buildings.
X	Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations; ground badly cracked Rails bent.
XI	Few masonry structures remain standing, Bridges destroyed,
XII	Damage total Lines of sight and level distorted. Objects thrown upward into the air.

SOURCE: U.S. Geological Survey, "The Severity of an Earthquake," brochure, 1990.

quake losses are concerned with what effects an earthquake might have on nearby communities. Earthquake engineers, for example, desire quantitative assessments of expected ground motion or deformation in order to evaluate the likely impact on buildings or lifelines.[9]

Ground Shaking

Contrary to the popular image in Hollywood movies or the more spectacular literary accounts, the earth generally does not open up and swallow buildings during earthquakes. Cracks and fissures do occasionally break the earth's surface. However, they are secondary effects of the most damaging earthquake phenomenon—strong ground shaking caused by seismic waves.

Analogous to sound waves,[10] seismic waves can be produced at different frequencies (corresponding to the pitch of a musical note) and at different amplitudes (corresponding to volume). Large earthquakes (which involve big motions on big faults) tend to produce larger amplitude, lower frequency waves. In reality, however, all earthquakes produce a complex suite of different waves of varying amplitudes and frequencies.

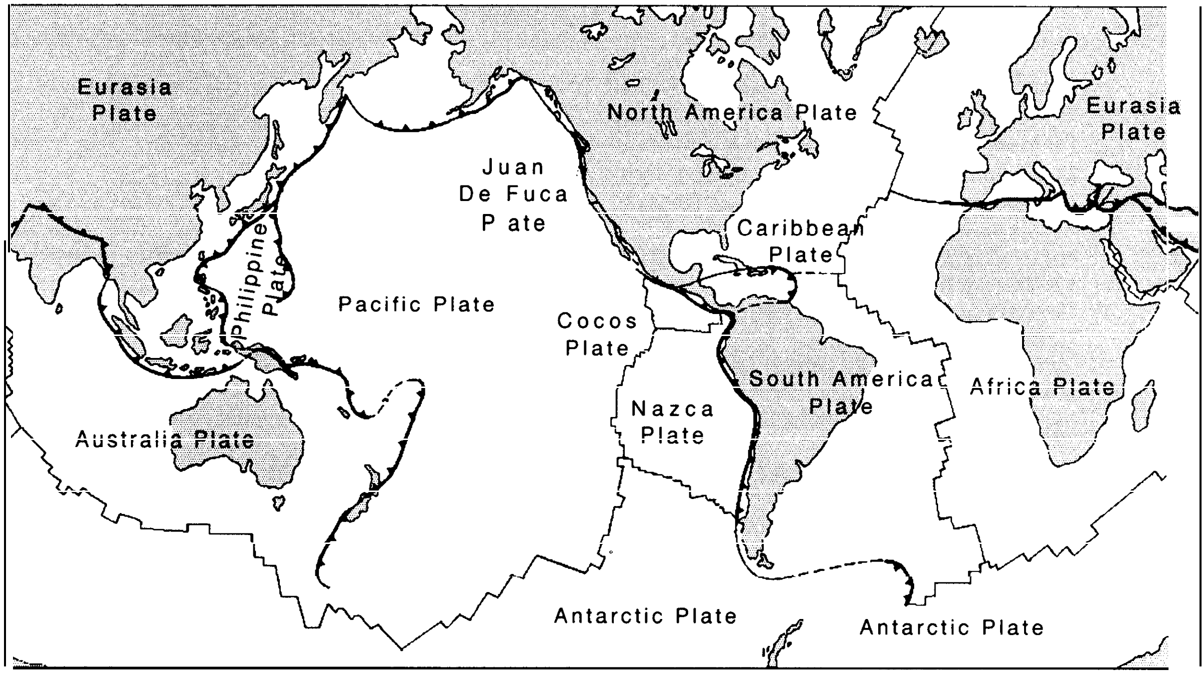
The damage done to structures and their contents depends on the characteristics of the ground motion. The shaking may be up and down, side to side, or some complex combination of the two. There may be a short flurry of rapid, energetic motions followed by rolling or swaying motions that last several seconds or more. Higher frequency accelerations[11] primarily affect shorter, stiffer structures; repetitive, lower frequency motions pose a special threat to very tall or flexible structures. Displacements produced by very large amplitude

[9] *Lifelines* are roads, bridges, communication systems, utilities, and other essential infrastructure. See chapter 3.

[10] One type of seismic wave, the *P-wave,* is in fact an underground sound wave.

[11] Acceleration is commonly expressed as a fraction of the strength of earth's gravity, *g* . A vertical acceleration of more than 1 *g* can actually throw objects in the air.

FIGURE 2-2: World's Major Tectonic Plates



SOURCE: Office of Technology Assessment, 1995, based on Bruce A. Bolt, *Earthquakes (New* York, NY: W.H. Freeman and Co , 1993), p 36

waves can stretch or twist structures beyond their engineering limits. The frequency, energy content, and duration of shaking are not related simply to earthquake size, but also to distance from the fault, direction of rupture, and local geology, including soil conditions.

Increasingly, earth scientists have applied state-of-the-art R&D to determining what sort of ground acceleration and displacement is to be expected in different earthquake regions. Such estimates require knowledge (or prediction) of what waves are originally generated by the earthquake (which implies an understanding of exactly how earthquakes occur) and of how these waves decay, grow, or combine as they travel through the earth. The latter requires geophysical and geological mapping of the rocks between the earthquake and the area of concern.

Because softer soils and clay tend to amplify ground motions, compared with those experienced on bedrock, research has also been directed at how seismic waves interact with surficial and near-surface materials to enhance ground shaking. A dramatic example of the effects of localized geology was the 1985 Mexico City earthquake; ground motions there were significantly enhanced at periods of several seconds compared with those at hard-rock sites closer to the quake source[12] (see box 2-2).

12 Thomas H. Heaton and Stephen H. Hartzell, "Earthquake Ground Motions," Annual Review *of Earth Planetary Science,* vol. 16, 1988, p. 124.

BOX 2-1: Geologic Settings for Earthquakes

Subduction Zones

In Alaska and the Pacific Northwest, the overriding of the North American continent over the various plates of the Pacific Ocean has led to the formation of *subduction zones,* a type of plate boundary that generally produces very large earthquakes. In a subduction zone, the layers of rock making up an oceanic plate move toward a landmass and, in the resulting collision, are forced down into the earth's deep interior. In the Pacific Northwest, this collision is responsible for the presence of the region's coastal mountains, for the volcanic activity that has produced the Cascade Mountain Range, and—most significantly—for the potential for major earthquakes to occur where the subducting plate is stuck, or locked, against the overriding continent. In most cases, this is at depths of 15 to 45 km (1 O to 30 miles).

Earthquakes in subduction zones generally reflect the presence of *thrust faults* ---fractures in the earth that allow one rock mass to slide toward and over its neighbor, The seismic waves thus generated shake the ground upward and downward as well as forward and back. Because the faults allow for vertical motions, subduction zone earthquakes can lead to the uplift or subsidence of local landmasses, over time flooding coastal areas or leaving them high and dry. If the earthquake occurs offshore beneath the ocean (the plate boundary in a subduction zone generally lies underwater and out of sight), the vertical motion of the sea bottom can send a surge of water (a *tsunami*) racing toward vulnerable seaside communities. Finally, since subduction zones are typically mountainous (because of all the vertical fault motion), strong subduction temblors can set off major landslides, avalanches, or mudflow.

Strike-Slip Plate Boundaries

A very different type of plate interaction is at work in California and southeast Alaska. Here, the Pacific Plate (on which Baja California and the westernmost sliver of the North American continent rest) slides sideways against the North American Plate in a motion known geologically as *strike-slip.* On a strike-slip boundary, there is very little up-and-down motion, most earthquake waves are side to side, and seismic activity does not raise mountains or produce tsunamis in the way it does in a subduction zone.

In the case of California, the seam between the North American and Pacific Plates is the San Andreas fault, a long and distinct scar in the earth's surface that runs beneath San Francisco, through central California, and southward toward Mexico through the desert east of Los Angeles. [1]There is another strike-slip plate boundary fault off the coast of southeast Alaska. Earthquakes occur along these faults primarily because relative motion, or *slip,* along either fault is not continuous over time or distance. That is, the fault is locked most of time, so that no slip occurs. The inexorable movement of the tectonic plates, however, causes stress to build along the fault until, for poorly understood reasons, one or more segments of the fault rupture, releasing the stored-up energy in an earthquake.

In California, most of the slip between the North American and Pacific Plates occurs along the San Andreas fault or in the immediate vicinity. Some deformation of the plate edges also occurs many miles from the primary fault, leading to stress-relieving earthquakes on strike-slip faults located on either side of the San Andreas. An example is the 1992 Landers earthquake (M7.3). The largest U.S. earthquake in 40 years, it occurred in a relatively sparsely populated area several miles northeast of Los Angeles.

[1] A continuous narrow break in the earth's crust, the entire fault zone is more than 800 miles long and extends at least 16 km beneath the earth's surface. Sandra E Schulz and Robert E. Wallace, The *San Andreas Fault*, prepared for the U.S. Geological Survey (Washington, DC. U.S. Government Printing Office, 1993), pp. 3-4.

(continued)

BOX 2-1 (cont'd.): Geologic Settings for Earthquakes

A pronounced bend in the San Andreas north of the Los Angeles area effectively locks the motion of the tectonic plates, contributing to vertical deformation and setting the stage for earthquakes on downward-dipping faults hidden from view beneath the earth's surface. The 1971 San Fernando and 1994 Northridge quakes both ruptured such "blind" thrust faults,

Intraplate Earthquakes

Although more than 90 percent of the world's earthquakes occur on plate boundaries, damaging earthquakes have also occurred in areas far from plate edges. *Intraplate* earthquakes, which though uncommon can be sizable, seem to reflect processes that are a topic of current tectonic and geophysical research Possible explanations include: 1) dynamic interactions between the earth's stiff exterior layers and its deeper, more flowing mantle; 2) a continent's adjusting to evolving plate boundary geometries (the Basin and Range Province of Nevada, for example, is stretching east-west following the disappearance of a subduction zone that once lay to the west); or 3) the interaction between zones of weakness within a plate and stresses transmitted across the plate from its boundaries,

The regions of the United States in which future intraplate earthquakes are most likely to occur are the Intermountain West and central United States, although parts of the Atlantic seaboard are also susceptible.[2] Compared with interplate earthquakes, uncertainty over the origin, likelihood, severity, and characteristics of intraplate quakes is very high, Improved understanding can come only through further basic earth science research.

[2] The eastern coast of North America, while marking the edge of the continent, is not a plate boundary North America is joined directly to the rocks underlying the western half of the Atlantic Ocean, and the eastern boundary of the North American Plate lies in the middle of the Atlantic.

SOURCE Office of Technology Assessment, 1995

Other Effects

The shaking caused by seismic waves, in addition to directly damaging structures, can also affect the earth's surface in ways equally detrimental (or more so) to the built environment. Ground failure, as these effects are often called, has several different facets:

- 1 iquefaction, whereby shaking transforms a water-saturated soil or sediment into a thick, quicksand-like slurry;
- ground rupture, in which shaking opens up fissures and cracks in the soil;
- surface faulting, in which an earthquake fault reaches the surface of the earth and produces vertical or horizontal *offsets* of material astride the fault;
- landslides or avalanches; and
- damaging water waves (e.g., tsunamis and seiches).[13]

[13] *Fast-moving* surges of water that travel across the ocean, *tsunamis* form a steep wall of water when entering shallow water along shorelines. The local wave height and run-up length are affected by the topography of the seafloor and continental shelf and by the shape of the shoreline—tsunamis with crests as high as 25 meters have devastated parts of Japan. Bruce A. Bolt, *Earthquakes (New* York, NY: W.H. Freeman and Co., 1993), pp. 148, 151. Tsunami generation is not fully understood, and may result more from the absolute motion of material at an earthquake fault than from the ground shaking from seismic waves. *Seiches are* earthquake-generated surges of water on lakes and enclosed bays.

BOX 2-2: Mexico City Earthquake

On September 19, 1985, Mexico City experienced the effects of an M8.1 quake that occurred in a subduction zone 350 km away Strong shaking caused extensive damage, killed thousands of people,[1] and left many more thousands homeless Most of the damage was confined to areas of the city built on soft, water-saturated soils

Key factors in the devastating losses Included:

- the long duration of shaking,
- local soil conditions that amplified seismic energy and produced extensive liquefaction,
- poor overall configuration and significant irregularities in the distribution of buildings mass, strength, and stiffness, and
- poor quality control of building materials.

Rupture on the segment of a subduction zone known as the Michoacan gap produced approximately 1 5 minutes of shaking with a roughly two-second period. (Higher frequency motions were damped over the distance between the earthquake's focus and Mexico City.)

Liquefaction was widespread, and soil-structure interaction increased the structural response of many multistory buildings to a period that coincided with the long-period motion produced by the quake. The effects of this resonance Included drift, deformation, and pounding between buildings

[1] The official count is 4,596 lives lost, although other estimates areas high as 20,000

SOURCE: Applied Technology Council and Earthquake Engineering Research Institute, *Proceedings of the Workshop for Utilization of Research on Engineering and Socioeconomic Aspects of the* 1985 *Chile and Mexico Earthquakes, ATC-30* (Redwood City CA Applied Technology Council), 1991

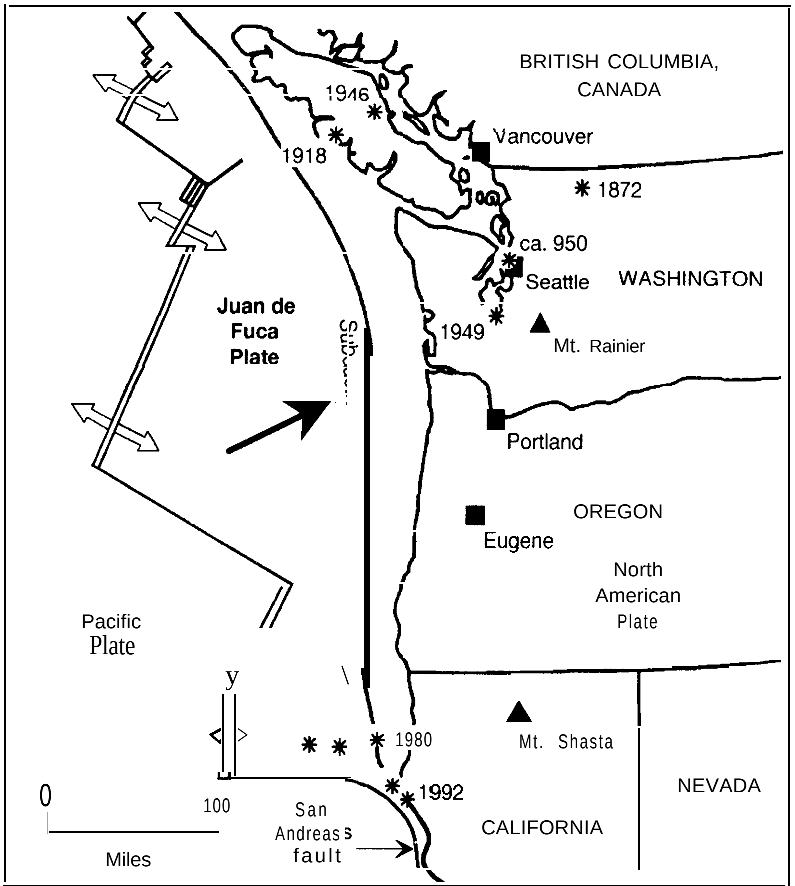
Like strong ground shaking, ground failure is strongly dependent on the surface and near-surface geology. Areas adjacent to waterways and developed with artificial fill are particularly susceptible to liquefaction, as seen in the Marina district in San Francisco during the 1989 Loma Prieta earthquake and in the 1995 Hyogoken-Nanbu earthquake that struck Kobe, Japan. Lateral spreading (in which surface layers are transported laterally over liquefied soils) ruptured water and sewer lines in the Kobe quake. The shaking produced by the 1994 Northridge, California, quake and its aftershocks caused thousands of landslides in nearby mountains.

SEISMIC HAZARDS ACROSS THE UNITED STATES

Earthquake researchers use an understanding of the basic setting for earthquakes and knowledge of prior earthquakes to assess seismic hazards and relate these to affected communities. Earthquake hazards vary widely across the country, from high in Alaska and the West Coast to low (but not zero) in much of the eastern United States. There is a continuum of earthquake risk,[14] as well: where heavy urbanization exists and frequent damaging earthquakes are expected, the risk is very high (e.g., in the San Francisco Bay or Los Angeles

[14] *Seismic hazard* is the potential for an earthquake and related effects to occur. *Seismic risk* is the likelihood for casualties, damage to the built environment, or other losses to occur as a result of earthquakes.

FIGURE 2-3: Tectonic Setting and Significant Earthquakes in the Pacific Northwest



NOTE * indicates earthquakes of magnitude greater than 7

SOURCE Office of Technology Assessment, 1995, based on U S Geological Survey

areas). In the Pacific Northwest, the seismic risk stems from the potential for infrequent but large to great earthquakes and from the region's status as a relative newcomer to mitigation (i.e., fewer steps have been taken to reduce risk). Likewise, central and eastern areas of the United States face the threat of significant earthquakes over very long intervals; the low frequency of damaging seismic events in recent history has contributed to the more limited implementation of mitigation measures than in the West, despite the vulnerability of many population centers (e.g., New York City or Boston) to even moderate shaking. The following sections describe current knowledge of earthquake hazards in different regions of the United States.

Pacific Northwest

The coastal area stretching from Alaska's western Aleutian Islands to the states of Washington and Oregon is at risk for both moderate and enormously powerful earthquakes. This area encompasses the growing metropolitan areas of Seattle, Portland, and Anchorage, as well as cities on Canada's west coast. Estimates of possible earthquake magnitudes in the region range as high as magnitude 9 (see figure 2-3).

The convergence of tectonic plates creates a high likelihood of seismic activity. For this reason, Alaska frequently experiences potentially damaging earthquakes, but due to its relatively low population density the impact is smaller than in more developed areas. In 1964, the second largest quake of this century struck Alaska, uplifting sections of the ocean floor and causing extensive damage to the Anchorage area. The Mw9.2 quake also caused a tsunami that led to further loss of life and damage in Alaska and in the northern California coastal town of Crescent City.

If such a temblor occurred further south, it could affect coastal communities from Vancouver, British Columbia, to northern California. However, off the coasts of Oregon and Washington, there have been no quakes of this size during recorded history. Awareness of this particular seismic threat was low until evidence of tsunami deposits and changes in coastal elevation, gathered in large part through NEHRP, revealed that great subduction zone earthquakes had occurred in the past. Based on tsunami records from Japan, the most recent may have been in the year 1700.[15]

Moderate-to-large crustal earthquakes in Oregon and Washington have been relatively infrequent, but the risk to population centers is significant. A major quake struck the Cascades of northern Washington in 1872;[16] the Puget Sound region experienced quakes of magnitudes 7.1 and 6.5 in this century;[17] and as recently as March 1993, a M5.6 temblor rocked the Oregon capital city of Salem.[18]

Uncertainty remains over how likely or how severe future events may be. Research into this question, much of it involving the modeling of geophysical processes in the region, is active and growing, and may eventually remove much of this uncertainty. In the meantime, complementary research into paleoseismology (the study of early historic or prehistoric earthquake activity based on geologic evidence) seeks to refine estimates of the timing and magnitude of previous subduction zone and crustal quakes. Besides indicating that prehistoric, devastating tsunamis occurred, the geologic record also suggests that a major earthquake took place 1,100 years ago directly beneath what is now downtown Seattle.[19]

California

A combination of high population density, heavy levels of urbanization, and the relatively frequent occurrence of moderate to great earthquakes makes California a state with very high seismic risk. Other areas in the United States may experience equally severe earthquake disasters, but the likelihood is lower.

For many years it was thought that the earthquake hazard in California stemmed primarily from the great San Andreas fault system, which accommodates the sliding of the North American continent sideways against the Pacific Plate. Several M8+ earthquakes have occurred along the San Andreas, including the great 1906 San Francisco Earthquake. The long-awaited “Big One” is ex-

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[15] Kenji Satake et al., “A Possible Cascadia Earthquake of January 26, 1700, as Inferred from Tsunami Records in Japan,” *Geological Society of America 1995 Abstracts with Programs*, vol. 27, No. 5, 1995, p. 76.

[16] Reported effects indicate that its magnitude was approximately 7.4, probably the largest during recorded history for that area. Thomas Yelin et al., *Washington and Oregon Earthquake History and Hazards*, U.S. Geological Survey Open File Report 94-226B (Denver, CO: National Earthquake Information Center, 1994), p. 7.

[17] The quakes took place in 1949 (M7.1) and 1965 (M6.5); both deep quakes (depths of 54 to 63 km), they caused several deaths and significant damage. Linda Lawrance Noson et al., *Washington State Earthquake Hazards*, Information Circular 85 (Olympia, WA: Washington Department of Natural Resources, 1988), p. 21.

[18] Six months later, a pair of strong quakes occurred a little more than two hours apart near Klamath Falls, in the southern part of the state. Shallow crustal quakes like these have also occurred in the Portland area. Yelin et al., see footnote 16.

[19] Ibid., p. 9.

ROBERT E. WALLACE, U.S. GEOLOGICAL SURVEY

Looking northwest along the San Andreas fault, the seam between the North American and Pacific Plates, in the Carnzo Plain (central Ca//forn/a)

pected to involve rupture of the fault's southern section.

A more recently recognized danger is the likelihood of future moderate-to-large earthquakes occurring on lesser known or even unsuspected faults adjacent to or directly underneath major metropolitan centers (see figure 2-4). The quake beneath Northridge in January 1994 revealed all too well the hazardous potential of blind thrust faults in the Los Angeles area.[20]

The danger of these blind thrust systems is a combination of the size of their associated earthquakes and their proximity to urban centers. Because an earthquake's damaging effects tend to decrease rapidly with distance, the physical separation between the San Andreas and a metropolitan center such as Los Angeles allows policy makers to prepare the built environment against a lesser amount of damage than sheer earthquake magnitude might seem to warrant. However, if a fault capable of producing earthquakes is close by, then its proximity allows even a moderate event to inflict more damage than might result from the long-awaited "Big One."[21]

In northern California, the geometric complexity of the San Andreas fault system that prevents North America from sliding cleanly against the Pacific Plate causes the San Andreas to branch off into a series of smaller faults that run in a north-south direction along the east side of San Francisco Bay (see figure 2-5). In addition to the 1906 San Francisco and 1989 Loma Prieta earthquakes, the Bay Area has experienced 20 other moderate to great earthquakes in the last 160 years .[22]

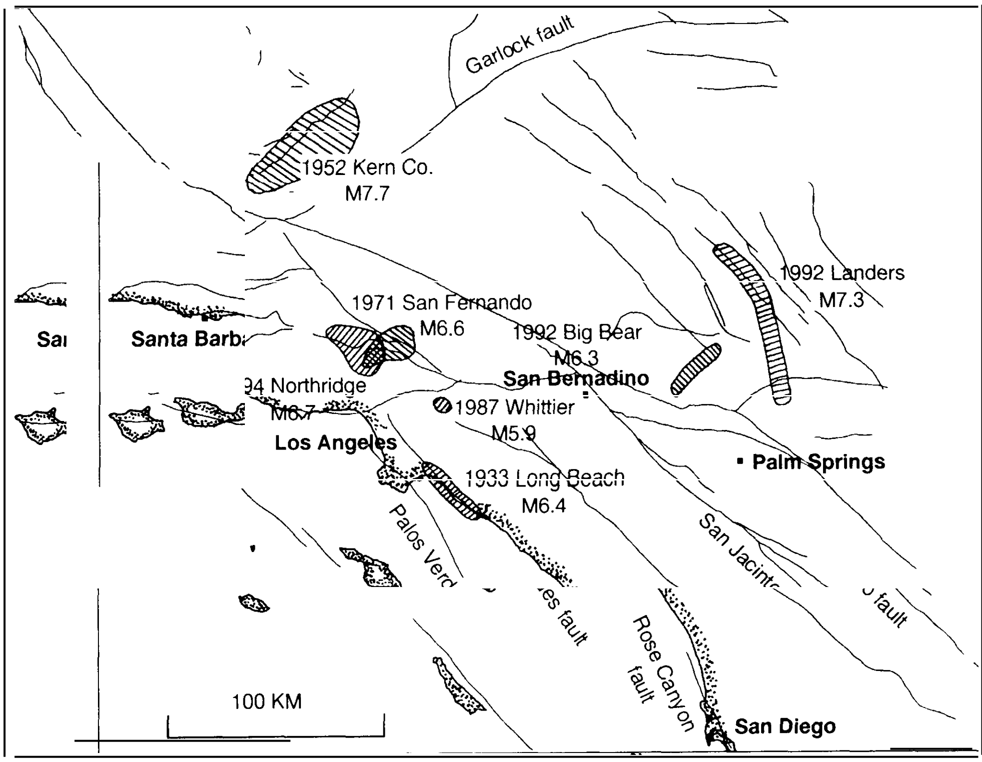
Because of these and other findings from recent research, the true earthquake hazard in California remains uncertain, and future estimates may well be subject to upgrading. As of 1990, **the estimated likelihood of major (M7+) earthquakes stands at 67 percent over 30 years in the San**

[20] Seismograph and strong-motion instrument data recorded during and after the Northridge earthquake indicate larger ground motions than have typically been observed or reflected in engineering design in California. The aftermath of the quake included realization that improved knowledge of the system of blind thrust faults lying beneath the Los Angeles area and environs would be useful for targeting mitigation efforts. While oil company studies are a good source of information about subsurface structure, the mapping rarely extends to depths where earthquakes initiate.

[21] It appears that one such fault, the Elysian park blind thrust fault, lies directly beneath downtown Los Angeles.

[22] Association of Bay Area Governments, 'The Bay Area Is Earthquake Country," Internet, address http: //www.abag.ca.gov/bay area/eq - maps; doc/text1.html#background, citing Jeanne B. Perkins and John Boatwright, *The San Francisco Bay Area--On Shaky Ground* (Oakland, CA: Association of Bay Area Governments, April 1995).

FIGURE 2-4: Earthquake Source Zones for Selected Significant Events in Southern California



NOTE: Shaded areas represent rupture zones for earthquakes shown

SOURCE U S Geological Survey, 1995

Francisco Bay area.[23] Studies of the potential for liquefaction and ground failure that would result from shaking on the San Andreas and its neighbors across the Bay are continuing,[24] as are investigations of local fault structures.

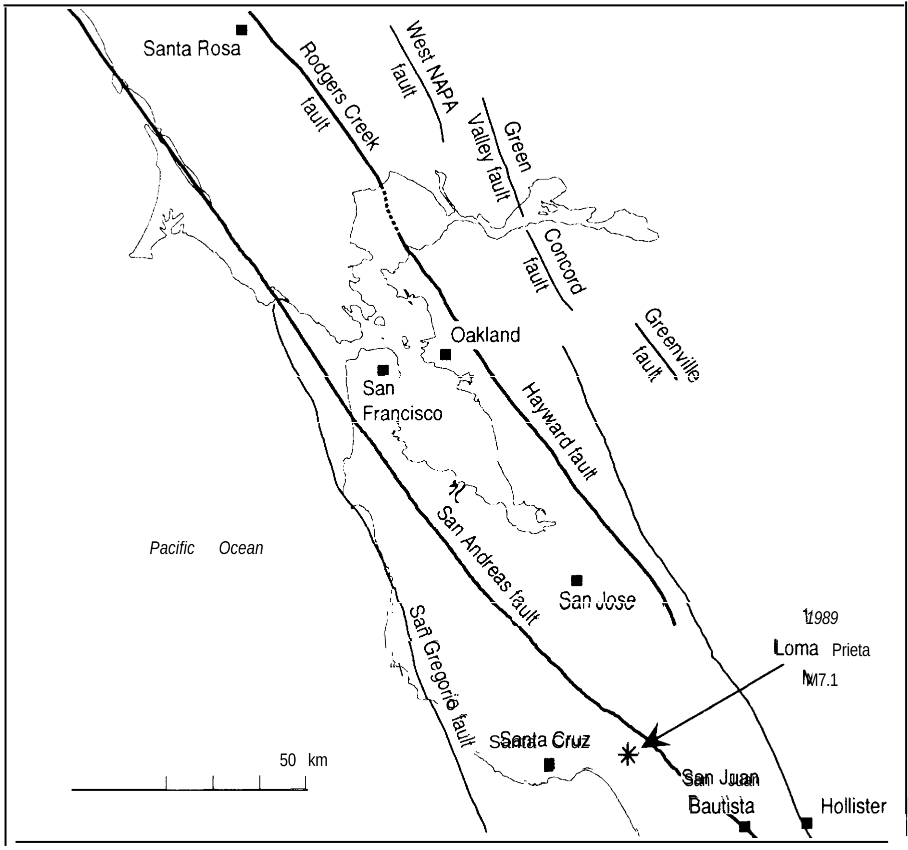
The 30-year probability of a major earthquake in southern California, estimated in 1994, is 80 to 90 percent (this estimate reflects both San Andreas and blind thrust hazards for the urban corridor from San Bernardino through Los Angeles to Santa Barbara).[25] Scientists have also noticed a historical deficit in the size or number of earthquakes expected for southern California;

[23]The primary fault structures evaluated for the assessment were nearby segments of the San Andreas fault and the neighboring fault system east of the bay, which consists of the Hayward and Rodgers Creek faults. Working Group on California Earthquake Probabilities, *Probabilities of Large Earthquakes in the San Francisco Bay Region, California,* U.S. Geological Survey Circular 1053 (Washington, DC: U.S. Government Printing Office, 1990), p. 31.

[24]This is an area of cooperation between USGS and the California Division of Mines and Geology, the state agency responsible for mapping special hazard zones.

[25]Working Group on California Earthquake Probabilities, "Seismic Hazards in Southern California: Probable Earthquakes, 1994-2024," *Bulletin of the Seismological Society of America,* vol. 85, No. 2, April 1995, p. 379; USGS and SCEC Scientists, "The Magnitude 6.7 Northridge, California, Earthquake of 17 January 1994," *Science,* vol. 266, Oct. 21, 1994, p. 396.

FIGURE 2-5: Primary Faults in the San Francisco Bay Area



SOURCE U S Geological Survey, 1995

geologic and geodetic data indicate that too few earthquakes have occurred to account for strain accumulation.[26] Whether this points to bigger quakes or to more frequent quakes is still under discussion in the scientific community.

Intermountain Seismic Belt

A region not commonly associated with seismic hazards—yet nevertheless under considerable risk—is the Intermountain Seismic Belt. Stretching from southern Idaho and western Montana down through southwestern Utah and Nevada, this area includes the urban center of Salt Lake City, Utah, and other rapidly growing communities in the Intermountain West (e.g., Boise, Idaho, and Reno, Nevada).

Earthquakes here do not stem from the plate collisional processes of the Pacific Northwest or from the sideways sliding of adjacent plates seen in California. Rather, they arise from intraplate deformation of the North American continent associated with the uplift of the Rocky Mountains

26 James F. Dolan et al., "Prospects for Larger or More Frequent Earthquakes in the Los Angeles Metropolitan Area," *Science*, vol. 267, Jan. 13, 1995, p. 203; and Working Group on California Earthquake Probabilities, see footnote 25.

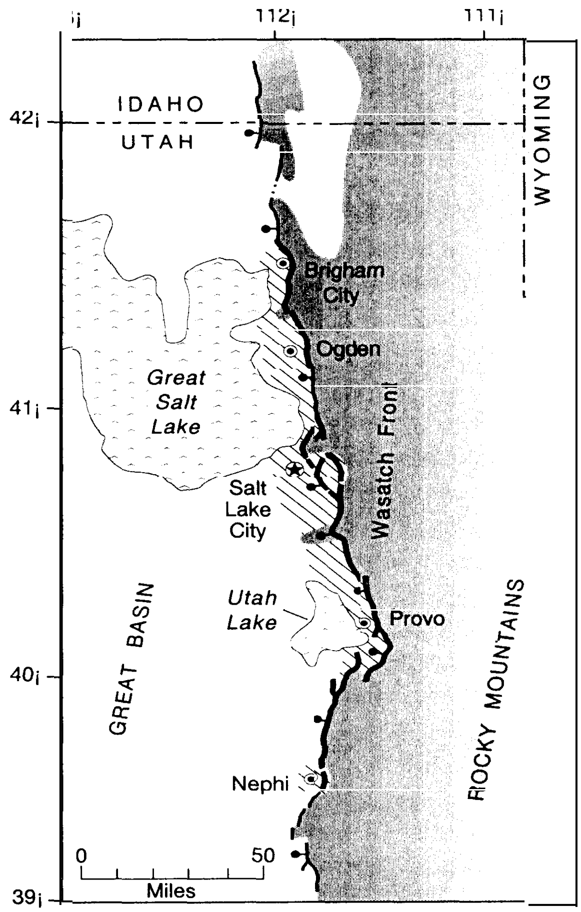
and the east-west stretching of the Basin and Range Province. Because this region lies within the interior of the North American Plate and far from the active deformation, collision, and sliding experienced at the plate edges, damaging earthquakes are relatively rare. However, since these earthquakes reflect active mountain-building processes in the continental interior, when they do occur, they can be sizable (M7 or higher).

Even though the maximum earthquake magnitudes in this region appear to be less severe than those projected or observed in the Pacific Northwest or California, the potential for disaster exists simply because the scarcity of historic earthquakes has led to a relatively low level of preparedness. General settlement of the area did not begin until the 1840s; in the intervening years, there have been no large quakes near the region's few urban centers. Consequently, damaging earthquakes have generally been less of a public concern than is the case in California. The region's last major quakes were in Montana in 1959, when several people were killed by landslides, and southern Idaho in 1983.

Awareness of the threat to Utah's metropolitan corridor grew as a result of a major NEHRP project to study the Wasatch Front, which is formed by the uplift of the Rocky Mountains along a long, north-south fault zone—the Wasatch fault zone (see figure 2-6). The research showed that major earthquakes *have* occurred in the past, with paleoseismic evidence suggesting a roughly 400-year recurrence along the most urbanized part of the Wasatch fault zone.[27] In 1991, **the probability of a** M7+ **earthquake anywhere along the Wasatch was estimated to be 13 percent over a 50-year period.**[28] An earthquake of that size anywhere along the fault zone will be felt throughout the system, and is likely to damage structures in the closest cities.[29]

Although a major earthquake in a California city would cause considerable damage and loss of life, an occurrence in less-prepared Utah could be

FIGURE 2-6: Wasatch Fault Zone



NOTE: Thick line designates the Wasatch fault About 80 percent of Utah's population, or nearly 16 million people, are at risk to movement of the fault.

SOURCE: U.S. Geological Survey, 1995

[27] Michael N. Machette et al., "Paleoseismology of the Wasatch Fault Zone: A Summary of Recent Investigations, Interpretations, and Conclusions," USGS Professional Paper 1500-A, November 1990, p. A55. Led by USGS and the Utah Geological and Mineral Survey, the project was completed in the early 1990s; seismic hazard and risk assessment continues today under state and local authorities.

[28] S. Nishenko, "Probabilistic Estimates for the Wasatch Fault," in *Proceedings of the National Earthquake Prediction Evaluation Council,* June 11-12, 1991, Alta, Utah, USGS Open File Report 92-249 (Washington, DC: U.S. Geological Survey, 1992), pp. 16-19.

[29] Kaye Shedlock, U.S. Geological Survey, Earthquake and Landslide Hazards Branch, personal communication, Apr. 15, 1995.

far worse.[30] Moreover, continued population growth in the region will likely lead to urbanization in areas relatively untargeted (until recently) by earthquake researchers; this raises the possibility of additional damage in areas currently unaware of their seismic hazard.

Central United States

A series of three great earthquakes occurred between December 1811 and February 1812 near New Madrid, Missouri, opening chasms in the earth, destroying the scattered settlements in the region, and causing sections of the Mississippi River to temporarily reverse and flow backward. Although there were no modern seismographic instruments available then to record the quakes' magnitudes, the level of destruction witnessed places these events among the most powerful ever.[31]

The challenge to the earth science community has therefore been to determine the likelihood of future damaging earthquakes in this region, and to decide whether the great New Madrid earthquakes were a geophysical fluke or the offspring of geologic conditions specific to the region.[32] In many respects, this task has been more difficult to perform than is generally the case in the western United States, because earthquakes in the central and eastern United States cannot be accounted for by classic plate tectonic theory. Compounding this difficulty is an observational problem caused by the presence of the Mississippi. Sediments carried by the river and deposited overland during floods over the eons have blanketed the region with kilometers of mud, sand, clay, and soil that effectively hide potential earthquake faults from view.[33]

About a decade ago, a major success was achieved in the identification of a geologic structure that appears tied to the region's earthquakes. This structure, the Reelfoot Rift, is a buried series of faults and anomalous rock formations formed 500 million years ago when tectonic forces tried but failed to split North America in two.[34] The rifting event in effect drew a wounding scar through the more-or-less contiguous landmass of the central and eastern United States. It is this singular zone of weakness (identified through geophysical surveys) that may account for the New Madrid earthquakes (see figure 2-7).

Thus, it appears that seismicity in this area is tied to a particular geologic structure, and is not expected to recur randomly elsewhere (see figure 2-7). However, scientists have also learned that any earthquakes that do occur in the eastern half of the United States will be felt far more widely than

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[30] A 1976 USGS study, for example, projected 14,000 fatalities in the event of a major Wasatch Front event. The Salt Lake area has since upgraded its seismic zone status and implemented hazard assessment and mitigation projects.

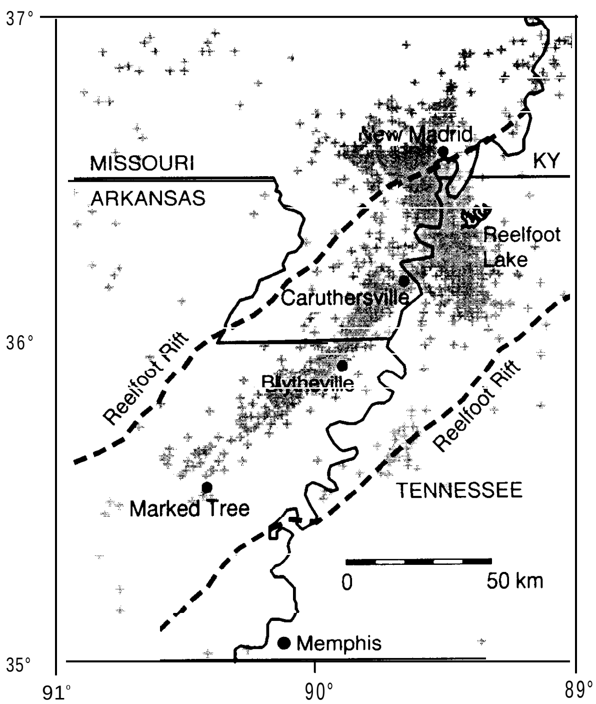
[31] With MMI of XI and XII, these temblors were the largest to occur within the coterminous United States; the 1812 quake was felt throughout an area of 5 million square kilometers. For comparison, the great San Francisco earthquake of 1906 had an MMI of XI and registered 8.3 the Richter scale. William Atkinson, *The Next New Madrid Earthquake: A Survival Guide for the Midwest* (Carbondale and Edwardsville, IL: Southern Illinois University Press, 1989), p. 22; and Bolt, see footnote 13, pp. 5, 270, 277.

[32] The former conclusion would suggest that a repeat might occur virtually anywhere in the United States; the latter, although disquieting to local residents, at least confines the likely region of future devastation.

[33] Although the deep sedimentary cap precludes direct observation of the faults, sedimentation facilitates paleoseismic work, and some information about the region's tectonic structures can be inferred by its topography. Geologic evidence indicates that three large earthquakes have occurred in the New Madrid area over the last 2,400 years, a recurrence rate comparable to that for the Wasatch fault or many reverse faults in California. Robert Yeats, Department of Geosciences, Oregon State University, personal communication, May 7, 1995; and see Keith I. Kelson et al., "Multiple Late Holocene Earthquakes Along the Reelfoot Fault, Central New Madrid Seismic Zone," *Journal of Geophysical Research*, forthcoming, January 1996.

[34] Robert M. Hamilton and Arch C. Johnston (eds.), *Tecumseh's Prophecy: Preparing for the Next New Madrid Earthquake*, U.S. Geological Survey Circular 1066 (Washington, DC: U.S. Government Printing Office, 1990), p. 9. At the time, North America was joined to Eurasia and Africa. Following the failure of the Reelfoot Rift, the landmass farther east split to form the proto-Atlantic Ocean.

FIGURE 2-7: New Madrid Seismic Zone



NOTE: Shaded area shows region of intense liquefaction in 1811 to 1812 earthquakes, small hatches represent seismicity during 1974 to 1991, and heavy dashed lines indicate boundaries of the Reelfoot Rift.

SOURCE U S. Geological Survey, 1995

quakes that occur west of the Rockies (see box 2-3).

Given the potentially far-flung and devastating effects of a major earthquake in the central United States, it is critical that earthquake severity and timing estimates are refined to the point that regional policymakers know the need and time scale for action. Unfortunately, uncertainties for the region remain substantial. Although the presence of the Reelfoot Rift provides an explanation for the siting of earthquakes, it does not by itself predict their occurrence. At present, there is no clear consensus on what mechanism causes tectonic stress in the region to build up to the point of an earthquake. In the absence of a conceptual tectonic model, the best guide to future earthquake activity in this region lies in the record of past earthquakes. This record suggests a recurrence of moderate quakes every 60 to 90 years (the last moderate event was in 1895).[35] **The probability of an M6.3 quake before 2040 is 86 to 97 percent; of an M8.3 quake, 2.7 to 4 percent.**[36]

Furthermore, outside the immediate New Madrid Seismic Zone, the characteristics of the source zones in the central (and eastern) United States are poorly known. The region is virtually devoid of identifiable active faulting,[37] and geologic studies of seismogenic features are in the reconnaissance stage. Although current levels of seismicity indicate a low hazard, NEHRP-supported studies have provided evidence of several major quakes in the Wabash Valley area (southern Indiana and Illinois) over the last 20,000 years.

Eastern United States

The Pacific Northwest, California, Intermountain West, and central United States have constituted the primary earthquake concerns in this country because the likelihood and potentially devastating effects of damaging earthquakes are known with greatest certainty in these regions. However. other parts of the country are also at risk (although the hazards are more uncertain) and may come more to the forefront with continued research and understanding. These regions include the Atlantic seaboard, which has experienced rare but moderately damaging earthquakes centered near Charleston, South Carolina; Boston, Massachu-

35 Atkinson, see footnote 31, p. 1; and ibid., P. 8.

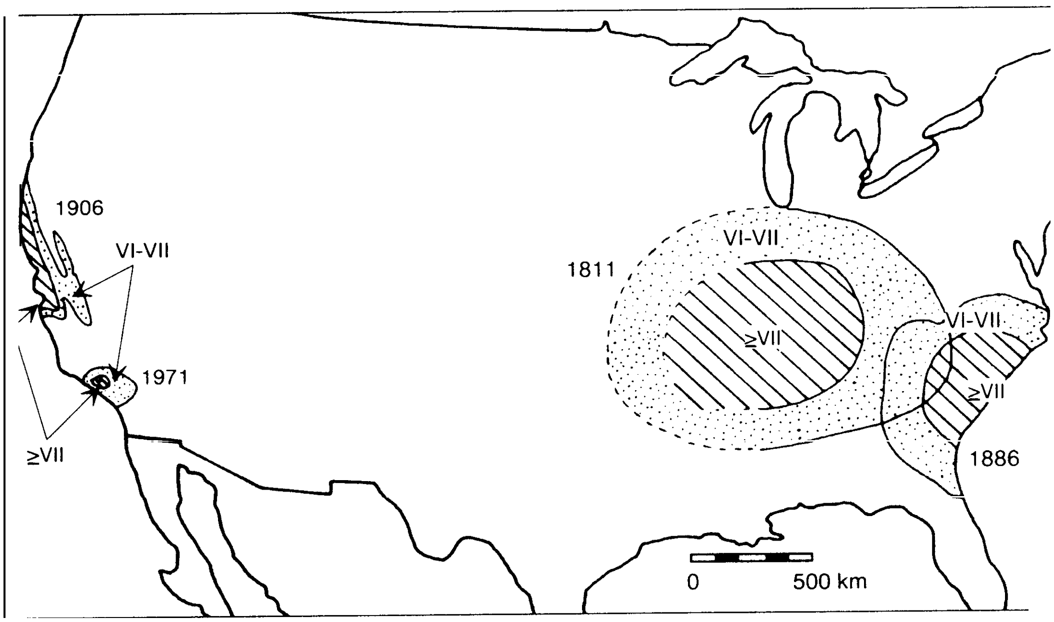
36 Hamilton and Johnson (eds.), see footnote 34.

37 Arch c. Johnston and susan J. Nava, seismic Hazard Assessment in the Central United States," Proceedings *of ATC-35 Seminar on New Developments in Earthquake Ground Motion Estimation and Implications for Engineering Design Practice, ATC-35-1,* Applied Technology Council (cd.) (Redwood City, CA: Applied Technology Council, 1994), p. 2-7. An exception is the Meers Fault in Oklahoma, which has geologic expression indicative of previous strong earthquakes but very low modem seismicity.

BOX 2-3: Relative Impact Areas for Eastern and Western Earthquakes

The two halves of the North American continent have very different tectonic histories. East of the Rockies, the North American landmass has held together (the abortive Reelfoot Rift notwithstanding) for a good part of the last billion years, and the tectonic plate material is strong In contrast, the continent west of the Rockies has experienced repeated breakup, reassembly, uplift, compression, extension, and shear—heating and weakening it Seismic waves radiating from a western earthquake therefore diminish more rapidly as they pass through fractured and heated rock, so that a major earthquake along the San Andreas can have relatively moderate effects on the distant Los Angeles basin. East of the Rockies, however, seismic waves are far less weakened as they radiate through hard, cold, strong rock, and even a moderate quake has the potential for destruction over a wide geographic range.[1]

Relative Impact Areas for Severe Earthquakes in Western and Eastern United States



NOTE: Figure shows areas of Modified Mercalli Intensity of VI and VII for two great earthquakes (New Madrid, Missouri, in 1811 and San Francisco, California, in 1906) and two major damaging earthquakes (Charleston, South Carolina, in 1886 and San Fernando, California, m 1971). Potential damage area corresponds to intensity VII and greater, an area of roughly 250,000 square miles for the New Madrid earthquake

SOURCE Off Ice of Technology Assessment, 1995, based on R Hamilton and A Johnston (eds.), *Tecumseh's Prophesy Preparing for the Next New Madrid Earthquake,* U S Geological Survey Circular 1066 (Washington, DC U S Government Printing Office, 1990) pp. 6, 12;O. W. Nuttli, "The MISSISSIPPI Valley Earthquakes of 1811 and 1812—Intensltles, Ground Motion, and Magnitudes" *Bulletin of the Seismological Society of America,* vol 63, 1973, pp. 227-248, and D W Rankin (ed.), "Studies Related to the Charleston, South Carolina, Earthquake of 188&A Preliminary Report, " U S Geological Survey Professional Paper 1028, 1977

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[1]The 1812 New Madrid shock was felt in Boston, Canada, Georgia, and at least as far west as Kansas and Nebraska Moderate ground shaking was felt over an area of nearly 1 million square miles, in contrast to some 60,000 square miles in the 1906 San Francisco quake. William Atkinson, *The Next New Madrid Earthquake: A Survival Guide for the Midwest* (Carbondale and Edwardsville, IL Southern Illinois University Press, 1989), p 18

SOURCE Office of Technology Assessment, 1995 setts; and northward toward the Saint Lawrence Valley.

Puerto Rico and the U.S. Virgin Islands are at risk from earthquakes in the Caribbean's subduction zone. In 1917, Puerto Rico suffered a major earthquake (M7).

Limiting Factors in Assessing Seismic Hazards

Damaging earthquakes have occurred in many parts of the United States, and several metropolitan areas are located in regions of moderate to very high seismic hazards (see table 2-3). Over the last quarter of a century, understanding of these hazards has increased considerably. In the past five years, advanced instrumentation and computer-based analytic tools have revolutionized earth science research and laid the groundwork for new hazard estimation capabilities.

Despite the many achievements to date, uncertainties still plague our ability to characterize seismic hazards. Engineers desire better information on the types of ground shaking expected for a given area so that methods for analyzing and improving a structure's seismic resistance can be enhanced. Likewise, planners and emergency managers would greatly benefit from improved knowledge of which areas in a city are likely to be hardest hit by future earthquakes. Factors that limit our knowledge of faults capable of producing earthquakes, of how often quakes occur on them, and of their likely effects include the following:

- The historical and instrumental records are very short compared with the time scales on which earthquakes are generated, particularly east of the Rockies.
- Most quakes begin rupturing 10 km or more beneath the surface of the earth: although some earthquake phenomena and causative factors are observed directly in surface faulting and geodetic strain, other information must be inferred from seismological and other data.
- Detailed mapping of the structural features that influence earthquake damage has been completed in only a small portion of the United States.
- There are few records of strong ground motions in close proximity to fault ruptures, and data on crustal deformation and stress are likewise sparse.

Such challenges to our understanding of seismic hazards and progress toward the long-term goal of accurately predicting earthquakes will likely be more readily surmounted in the future, given the present confluence of new tools, trained scientists, and expanded databases. These advances stem from work in the earth sciences supported by NEHRP and from other federal, state, local, and international activities.

EARTHQUAKE-RELATED RESEARCH IN EARTH SCIENCE

The preceding sections outlined some of the substantial progress made by the earth science community in achieving a basic understanding of the earthquake problem. This understanding has made it possible for policymakers to identify future trouble spots and to take preventive action. Current knowledge of seismic hazards in different regions, however, has not reached the point where scientists and policymakers are no longer surprised by earthquakes and their effects. Scientific uncertainties for much of the country remain high enough to discourage the implementation of oftentimes costly mitigation measures. Under NEHRP, earth science researchers seek to reduce these uncertainties and to make available much needed information for the implementation of seismic risk reduction policies, practices, and technologies. This section discusses current research efforts that address the primary knowledge gaps.

Objectives

The objectives of current earthquake-related earth science include:

- identifying the regions of potential risk;
- producing or refining estimates of future earthquake location, timing, and severity;
- highlighting special geologic hazards that may accompany future events (e.g., landslides, tsunamis, unusual ground shaking); and

TABLE 2-3: Summary of U.S. Earthquake Hazards

Area	Frequency/probability of return	Comments on tectonic framework
Alaska	Since 1900, one M8 or larger quake every 13 years, one M7+ quake every year, and several moderate to large quakes every year.	Subduction zone along Aleutian Islands, Alaskan Peninsula, and southern Alaska. Frequent strong intraplate seismicity. Damaging quakes also possible on strike-slip Queen Charlotte fault in southeast Alaska.
Pacific Northwest	90-year return period for a M7.5.	Shallow crustal quakes, massive subduction zone quakes possible offshore, and quakes within subducted plate deep beneath Puget Sound.
Northern California	67 percent chance of a M7 or greater earthquake in the San Francisco Bay area by 2020.	Primary faults: strike-slip San Andreas and Hayward/Rogers Creek faults on the east side of the bay; quakes on local blind thrust faults also possible, Northern California coast subject to quakes with several sources: northern segment of the San Andreas, Cascadia subduction zone, and inland crustal quakes.
Southern California	80-90 percent probability of a M7 or greater earthquake before 2024 in greater Los Angeles area.	Extensive rupture of strike-slip San Andreas possible, and moderate-to-large quakes also likely on secondary fault systems, Extensive buried thrust fault system beneath the Los Angeles basin as a result of compressional terrain Faults near Los Angeles' and San Diego's port facilities pose a similar threat as the fault that ruptured near Kobe, Japan, in 1995.
Hawaii	Frequent seismicity associated with volcanic activity; last major quake (M7.1) in 1975.	Repeatedly struck by tsunamis; landslide potential high,
Intermountain West	30 percent chance of major quake anywhere along Utah's Wasatch fault zone in the next 100 years. Growing population centers elsewhere in Intermountain Seismic Belt also susceptible to damaging earthquakes.	Mountain-building region; normal faulting with large vertical offsets possible from Utah northward through Idaho and into Montana.
Central United States	40-63 percent probability of recurrence of M = 6+ quake in New Madrid Seismic Zone before 2005, 86-97 percent probability before 2040, approximately 250-year return period for a M7.6 or greater	Abundant seismicity in New Madrid Seismic Zone, linked to rifted margin; dispersed seismicity elsewhere in the region not linked to specific faults,
Northeast	300-year return period estimated for a M7 Last moderate quakes in New York area in 1944 and 1985.	"Stable" plate interior, with zone of relatively high seismicity from Adirondacks up through St Lawrence Valley; dispersed seismicity elsewhere. Several large earthquakes scattered throughout region since 1600s, primarily in Canadian provinces,
Southeast	Charleston, South Carolina, struck by large quake (M6.7) in 1886. High concentration of seismicity in eastern Tennessee	Tectonic origin for seismicity in eastern United States unclear
Puerto Rico and U.S. Virgin Islands	Last major quake in 1917; estimated 70-year return period.	Subduction zone where the Caribbean Plate meets the North American and South American Plates

SOURCES: Working Group on California Earthquake Probabilities, Probabilities of large *Earthquakes in the San Francisco Bay Region, California,* U.S. Geological Survey Circular 1053 (Washington, DC U S Government Printing Office, 1990), Working Group on California Earthquake Probabilities, "Seismic Hazards in Southern California. Probable Earthquakes, 1994 to 2024, " *Bulletin of the Seismological Society of America,* vol *85, No 2,* April 1995, pp. 379-439; R. Hamilton and A Johnston (eds.), *Tecumseh's Prophecy: Preparing for the Next New Madrid Earthquake,* U.S. Geological Survey Circular 1066 (Washington, DC U.S. Government Printing Office, 1990); K Shedlock and C Weaver, *Program for Earthquake Hazards Assessment in the Pacific Northwest,* U S Geological Survey Circular 1067 (Washington, DC: U.S. Government Printing Office, 1991), and Christine A Powell et al , "A Seismotectonic Model for the 300-Kilometer-Long Eastern Tennessee Seismic Zone, " *Science,* vol 264, Apr. 29, 1994, pp. 686-688

- supporting scientific and engineering applications of earthquake data and theories.

Meeting these objectives and resolving some of the unknowns laid out in the first half of this chapter requires continued effort in several research disciplines. This work ranges from exploratory research into details of earthquake sources to applying new computational techniques toward predicting ground failure or tsunami development. **Earth science research and data collection efforts have been—and will continue to be—essential to the development and selection of mitigation options appropriate to a particular region's seismic risk.**

For the discussion that follows, earthquake-related research is grouped into two broad areas: 1) basic research into the fundamental processes that govern earthquake timing, location, and severity; and 2) research applied toward predicting the effects of earthquakes, which in turn supports engineering analyses, land-use planning, and emergency response.

Foretelling Earthquake Timing, Location, and Severity

The general theory of plate tectonics, while identifying where earthquakes should occur over the long term, does not itself give clear warning of earthquake likelihood or timing. This stems from the difference between geologic time, which spans thousands or millions of years, and the time scales that are appropriate for public policy. Plate tectonics suggests that if we were to wait several millennia, we would expect earthquakes to occur essentially everywhere along a plate boundary. What it does not tell us is which specific parts of that boundary will become active in the next few years or decades. Moreover, plate tectonics does not easily explain why earthquakes should occur far from plate boundaries (as they do east of the Rockies), and rising evidence suggests that the theory is generally inadequate to describe the large-scale tectonic behavior of continental masses.[38]

To specify which part of a plate boundary is likely to break in the near future, researchers must go beyond the large-scale workings of the basic plate tectonic model and identify how general plate tectonic movements are translated into local earthquakes. This quest entails a host of separate research endeavors, the chief of which are regional tectonic studies, including geodetic studies; fundamental seismological research and monitoring; and paleoseismology. The following sections describe these research areas.

Regional Tectonic Studies

Regional tectonic studies seek to determine how large-scale plate motions produce finer scale patterns of stress and deformation (e.g., uplift and compression of the earth's surface) in potential earthquake zones. If earthquake-causing buildup of tectonic stress can be correlated with the occurrence of tectonic deformation, areas of potential danger can be identified even in the absence of historical seismicity through observing changes in stress. Such an identification would be particularly useful in regions such as the Pacific Northwest where major earthquakes have been historically infrequent.

Tectonic studies also seek to identify hidden structures that are capable of producing earthquakes (e.g., Los Angeles' blind thrust faults) through a combination of remote geophysical techniques and onsite geologic mapping.[39] For example, scientists have studied how the relation-

[38] Current indications are that the thinner oceanic parts of the earth's surface act more plate-like (i.e., they are rigid and strong) but that continents behave in a more complex fashion. For example, the Basin and Range Province of Nevada is stretching in an east-west direction (generating low-level seismicity in the process), while the central and eastern parts of the country seem to consist of strong rigid blocks criss-crossed with weaker scars from ancient tectonic activity.

[39] Methods of imaging subsurface geology and seismogenic structures include analysis of the passage of seismic waves through the earth, and local changes in the earth's magnetic and gravitational fields. When combined, the data reveal variations in material properties or rock types that point to the presence of faults.

BOX 2-4: Geodetic Techniques

Japan initiated the first geodetic monitoring program at the turn of the 20th century, many decades before a similar program was established in the United States.[1] Today, both countries have implemented state-of-the-art observation systems intended to reveal strain and stress accumulation from ongoing tectonic processes. Although geodetic measurements are now made in many areas, in only two areas—the San Andreas strike-slip fault zone and the subduction zone along the southern coast of Japan—are there sufficient data to attempt to reconstruct the entire quake-loading cycle.[2]

Very Long Baseline Interferometry and Global Positioning System

The paucity of data stems in part from the logistics of geodetic measurement techniques, which for years required laborious field surveys. However, the availability of highly accurate clocks and digital telecommunications systems has brought significant advances to the field during the last decade or so. Very Long Baseline Interferometry (VLBI) and, later, Global Positioning System (GPS) satellites have allowed expanded observation of crustal deformation and measurement of slip rates with greater accuracy.[3] GPS-based techniques in particular offer speedier calculations of relative distances and thus deformations. Other technical advantages of GPS systems are: absence of line-of-sight constraints, simultaneous determination of vertical and horizontal position, and a useful interstation range from hundreds of kilometers to less than one kilometer.[4]

Regional networks of continuously recording GPS receivers are operating in Japan and California to monitor strain for earthquake research and forecasting. Deployment of portable stations after an earthquake allows scientists to observe post-seismic deformations; these data complement data from seismographs concerning the depth, orientation, and amount of fault slip.[5]

[1] Christopher H. Scholz, *The Mechanics of Earthquakes and Faulting (New* York, NY: Cambridge University Press, 1990), p 223

[2] Ibid., p 227.

[3] VLBI uses radio waves from distant quasars as sources of ranging signals. GPS satellites broadcast time-stamped position data at two different frequencies, allowing for correction of signal delays caused by the earth's atmosphere and thus Improved resolution

[4] Robert A. Page et al., *Goals, Opportunities, and Priorities for the USGS Earthquake Hazards Reduction Program,* USGS Circular 1079 (Washington, DC: U.S. Government Printing Off Ice, 1992), p 9

[5] University Navstar Consortium, *Geoscientific Research and the Global Positioning System. Recent Developments and Future Prospects* (Boulder, CO: 1994), pp. 3-4. The University Navstar Consortium (UNAVCO) provides information, support, and scientific infrastructure to principal investigators making use of GPS satellites for earth science and related research.

ship between primary tectonic features such as the Reelfoot Rift and the continental interior's overall stress regime may serve to localize seismicity in the New Madrid area.[40] Such research may also help to explain the spatial and temporal earthquake clustering that has been observed in the United States and other parts of the world.

Geodetic Studies

A number of technologies (see box 2-4) are used to observe and measure tectonic deformation. These geodetic studies provide part of the raw material for tectonic studies and serve as intermediate checkpoints for earthquake forecasts based on

[40] A current hypothesis is that most stable continental quakes occur through the reactivation of relatively young rift faults that break the integrity of the continental crust. John Adams and Peter W. Basham, "New Knowledge of Northeastern North American Earthquake Potential," ATC-35-1, p. 3-7, citing Coppersmith et al., *Methods for Assessing Maximum Earthquakes in the Central and Eastern United States: EPRI Project 2556-12,* Working Report (Palo Alto, CA: Electric Power Research Institute), 1987; and A.C. Johnston, "The Seismicity of 'Stable Continental Interiors'" *Earthquakes at North Atlantic Margins: Neotectonics and Postglacial Rebound, S.* Gregerson and P.W. Basham (eds.) (Dordecht, Netherlands: Kluwer Academic Publishers, 1989), pp. 299-327.

BOX 2-4 (cont'd.): Geodetic Techniques

Synthetic Aperture Radar Imagery

An even more recent departure from established ground-based geodetic measurement techniques is the use of remote sensing to produce detailed images of deformation fields. Microwave signals generated by synthetic aperture radar (mounted on aircraft or satellites) and reflected off the ground are processed to estimate displacement.[6] Unlike most geodetic techniques, a surveyed network need not be in place prior to an earthquake-satellite images collected at regular intervals can capture co-seismic displacements without advance knowledge of an earthquake's location.[7] Other advantages of Synthetic Aperture Radar imagery include more dense spatial sampling and better precision than previous space imaging techniques.

Laser Interferometry

Near Parkfield, California, the U.S. Geological Survey has been using a two-color laser distance measuring instrument (geodimeter) to observe relative movement in the vicinity of the San Andreas fault. The two-color geodimeter measures distances to a precision of 0.3 to 1.0 mm for ranges between 1 and 9 km.

In-fault Measurements

A number of instruments placed at various depths in an active fault zone also help to reveal ongoing deformation either directly (eg., through creepmeters and strainmeters) or indirectly (e.g., through changes in water level or pore pressure). Creepmeters continuously monitor fault movement within a few meters of fault zones to characterize the rate and nature of fault slip. They can detect changes of about 0.1 mm. Borehole volumetric strainmeters can detect changes of 10 parts per billion (1 inch in 1,600 miles) for signals with periods of several weeks and, for higher frequency signals, can detect even smaller changes.

[6] William Prescott, "Seeing Earthquakes from Afar," *Nature,* vol. 364, July 8, 1993, pp. 100-101.
[7] Didier Massonnet et al., "The Displacement Field of the Landers Earthquake Mapped by Radar Interferometry," *Nature,* vol 364, July 8, 1993, p 138

SOURCES: Office of Technology Assessment and U.S. Geological Survey, 1995.

models of regional tectonics. For example, geodetic data are used to infer rates of regional plate motion that, along with seismologic or geologic evidence of fault locations, can provide estimates of the hazard from these faults.[41] Important data are also obtained from strain measurements at depth (e.g., through borehole monitoring of porosity).

The advent of space-based geodetic techniques, such as Very Long Baseline Interferometry, Satellite Laser Ranging, and most recently, surveys using the Global Positioning System (GPS), has revolutionized this field of study.[42] With these newer techniques, it is possible to directly observe crustal deformation, which may ac-

[41] USGS and SCEC Scientists, see footnote 25, p. 395.

[42] The first two technologies were developed under the aegis of the National Aeronautics and Space Administration's (NASA) Crustal Dynamics Project, a program aimed at directly measuring the relative velocities of tectonic plates on a global scale; the original geoscientific applications of GPS stemmed from this work. University Navstar Consortium, *Geoscientific Research and the Global Positioning System: Recent Developments and Future Prospects* (Boulder, CO: 1994), p. 1. Today, under NASA's Mission to Planet Earth Program, space-based geodetic technology development and research continues.

celerate the development of reliable earthquake forecasting.

Fundamental Seismological Research

To better understand how stresses in the earth eventually lead to the rupturing of a fault and the production of an earthquake, scientists monitor earthquakes via global and regional seismic networks (coordinated systems of sophisticated seismic listening and measuring devices, known as *seismometers*; see box 2-5) and compare the seismology data collected with results from theoretical and laboratory models of earthquake generation.

Questions central to seismological research include the following:

- How does an earthquake initiate?
- What determines whether a growing earthquake becomes large, moderate, or small?
- Can a prenascent earthquake telegraph its future birth and characteristics to attentive observers?
- How does an earthquake affect tectonic stress in a region (e.g., does it simply alleviate stress and thus reduce the likelihood of an imminent recurrence, or can an earthquake create distortions in the regional stress field that set off nearby followers)?

The advent of faster, more powerful computers has aided in understanding the processes by which crustal stresses lead to earthquakes at any given location. Using seismological data, researchers now model how fractures initiate and propagate as a result of mechanical properties (e.g., frictional strength) and stress changes at each point on the fault. In addition, three-dimensional models of ruptures along segmented faults are being developed to study what stops earthquakes and thereby to estimate their magnitudes.[43]

Another effort to understand what controls earthquake faulting involves laboratory studies of the physical properties of earth materials and physical conditions at the earthquake source, the interactions between rock and fluid in the fault, and nucleation and instability mechanisms.[44] The objective is to improve tools for interpreting observations of seismic and geodetic data in terms of earthquake processes and conditions at the source.

Paleoseismology

On most faults, the time between similar large earthquakes is much longer than the period over which modern instruments have observed earthquakes and geodetic changes. Even in regions where recorded history spans thousands of years, such as the eastern Mediterranean or north-central China, contemporary observers often could not correlate earthquakes with specific faults.[45] Thus our knowledge of how often faults can produce damaging earthquakes is very limited.

To learn whether or not earthquakes consistently rupture the same segment of a fault in the same way (i.e., act as a characteristic earthquake) or follow a regular time pattern, it is necessary to extend the modern record back long enough to encompass several similar earthquakes on the same fault. This need led to the development of paleoseismology, a relatively new field of earth science. Researchers seek and examine evidence of sudden coastal subsidence or uplift; fault displacement revealed by shallow excavations; and deposits related to liquefaction, tsunamis, or other seismically induced processes. In many cases, paleoseismic events can be dated by radiocarbon and other techniques, although typically not with as much precision as historical events.[46]

With funding from NEHRP, this type of data collection has accelerated in the past 15 years. Paleoseismology has been particularly useful in as-

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[43] Ruth Harris, U.S. Geological Survey, Menlo Park, personal communication, Nov. 4, 1994.

[44] James Dieterich, U.S. Geological Survey, Menlo Park, personal communication, Nov. 4, 1994.

[45] This section is drawn from Robert Yeats, Department of Geosciences, Oregon State University, personal communication, May 7, 1995.

[46] Kenneth A. Geottel, Goettel & Horner, Inc., personal communication, May 7, 1995.

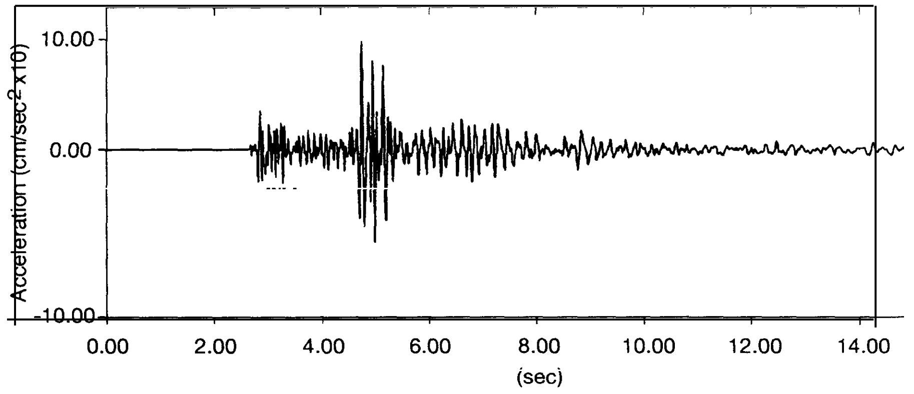
BOX 2-5: Seismic Monitoring

Seismic monitoring serves several purposes: it allows determination of the location of significant earthquakes in support of emergency response and public information; it enables nuclear test ban verification; and it supports research directed at improving basic understanding of tectonics and earthquake phenomena,

In the 19th century, knowledge of major seismicity was for the most part limited to earthquakes felt on the continents.[1] The installation and operation of seismometers in many countries, along with extensive cooperation in exchanging data, have since permitted knowledge and illustration of global patterns of seismicity, The 1960s witnessed the establishment of a global network of seismic stations (largely with nuclear monitoring in mind); at the same time, several regional seismic networks were established in the United States. As of 1994, there were more than 1,400 permanent seismographic stations maintained by regional networks [2]

Two primary classes of seismometers exist today: 1) 1960s-generation equipment that provides data in limited frequency and amplitude ranges, largely because of analog transmission constraints; and 2) new generation broadband, high-dynamic range instruments available since 1985. The advanced instruments and digital telemetry now enable improved representation of the phase and energy spectra of seismic waves, essential to ground motion and earthquake processes research. With constrained resources, however, there are tradeoffs between increasing the quality or the quantity of instruments Likewise, there is tension between providing funding for the operation and maintenance of stations and performing research with the available data.

Seismogram of Northridge Aftershock



NOTE: Vertical component of acceleration recorded in the San Fernando Valley from a magnitude 45 aftershock of the 1994 Northridge earthquake

SOURCE: U.S. Geological Survey, 1995.

[1] Bruce A. Bolt, *Inside the Earth" Evidence from Earthquakes* (San Francisco, CA W H Freeman and Co , 1982), p 54

[2] Council of National Seismic System, "CNSS Seismic Networks and Data Centers" internet address http://www. geophys.washington.edu/CNSS/cnss.sta.html, May 11, 1995 CNSS was begun at a meeting in Denver in February 1993 by representatives from most of the U.S. regional seismic networks and the National Seismic Network to help coordinate efforts to record and analyze seismic data in the United States As of spring 1995, 27 institutions had formally joined the council

(continued)

BOX 2-5 (cont'd.): Seismic Monitoring

National Seismic Network

In the late 1980s, the Nuclear Regulatory Commission decided to withdraw support for its networks, located primarily in eastern states, The U.S. Geological Survey proposed to establish the National Seismograph Network (NSN), a 150-station network of modern digital stations distributed throughout the country, to enable uniform monitoring of significant quakes and provide data for research into a variety of earthquake problems. To date, 23 NSN broadband seismic stations have been installed in the eastern United States, with nine more stations planned. In the western United States, 16 NSN broadband stations are operating, and seven more are planned. Installation of an additional 10 to 15 cooperative NSN stations is possible over the next few years for the continental United States.[3]

NSN is not intended to perform the monitoring and research functions of the existing regional networks, Rather, it leverages their capabilities with technology for recording broadband, high-dynamic range, three-component seismic data in real time and with low telemetry costs. In addition, NSN provides standardized data manipulation procedures and a communications network that interconnects regional networks[4]

[3]Harley Benz, U S Geological Survey, personal communication, May 11, 1995

[4]Thomas H. Heaton et al., "National Seismic System Science Plan, " U S Geological Survey Circular 1031 (Washington, DC: U.S. Government Printing Office, 1989), pp. 21-22

SOURCE Office of Technology Assessment, 1995

sessing earthquake potential in regions that have not been struck by a major earthquake during recorded history, such as the Salt Lake City metropolitan corridor, the San Andreas fault in southeastern California, and the Cascadia subduction zone in the Pacific Northwest. It has also helped to reduce uncertainty about the frequency of major quakes in the central United States, and to enhance knowledge of historic earthquakes in the San Francisco Bay area.[47]

Earthquake Forecasting and Prediction

A longstanding objective of efforts to understand basic geological and seismological processes is a reliable means of predicting earthquakes.[48] The simplest model of the earthquake cycle is that strain accumulates, is released in an earthquake, and accumulates again—initiating another cycle. The average length of the cycle for a certain type of quake at a given location is called the recurrence interval, which is used to roughly estimate the time of the next earthquake. To determine this interval, scientists rely on seismic monitoring and paleoseismology to obtain relationships for magnitude and recurrence.

Historical seismicity and paleoseismology show, however, that there is great variability in the timing, location, and magnitude of earthquakes. The variations in earthquake characteristics on a single fault segment or the clustering of several

[47]In spite of the fact that *paleo* means ancient, paleoseismologists study both prehistoric and historical earthquakes-in areas having short historic records, there may be only one example of an earthquake on a given fault. Carol Prentice and Andrew Michael, U.S. Geological Survey, Menlo Park, personal communications, June 5, 1995.

[48]This report distinguishes between forecasting and prediction as follows: the former refers to estimates of earthquake potential or timing over a period of many decades; the latter encompasses estimates of earthquake occurrence on shorter time scales (e.g., imminent—a few seconds or minutes; short-term-several minutes to days or weeks; and intermediate-term-up to several years).

TABLE 2-4: Comparable Seismic Zones

U.S. region	International counterpart
New Madrid Seismic Zone and eastern United States	Australia, peninsular India
California	New Zealand, northeastern Iran, Mongolia, Turkey, Venezuela
Intermountain West	North-central China, Aegean region of Greece and western Turkey
Pacific Northwest	Southwest Japan, southern Chile

SOURCE Robert Yeats, Department of Geosciences, Oregon State University, personal communication, May 7, 1995

earthquakes in time indicate that the simple model is not sufficient for many applications. Some areas exhibit greater variability than others; typically, these are regions of more complex geology and plate interaction. Several U.S. metropolitan centers are located in such regions (e.g., Los Angeles, San Francisco, and cities in the Pacific Northwest).

To improve on the simple earthquake model requires a better understanding of the processes through which tectonic stress leads to individual earthquakes. This entails developing models of earthquake generation and relating these models to things we can observe in the earth (some of which may turn out to be earthquake precursors). Therefore, current efforts at earthquake prediction combine historical seismological and paleoseismological data with models of earthquake generation, and correlate the results with measurements of geophysical phenomena.

Forecasts

In a few regions of the country, scientists have gathered enough data to permit long-term earthquake forecasts; these are often expressed as the probability that a certain size earthquake will occur within the next few decades, either for a single fault (e.g., the southern San Andreas or Wasatch) or for a region with several hazardous faults (e.g., the San Francisco Bay area).[49] Such probabilistic assessments have been important in analyzing a region's seismic hazard, and directly support land-use planning and building code development.[50]

Because individual earthquakes repeat so infrequently and because there is variability between events, these forecasts are subject to considerable uncertainty. We can develop and test improved models more rapidly if we also look outside the United States for data, especially to other parts of the world that have similar geologic settings and have had large historical earthquakes. Table 2-4 lists these areas and their international counterparts.

Prediction

In theory, prediction could stem from improvements to the probabilistic forecasting method—that is, through reducing uncertainties in the assessment of earthquake characteristics and timing to permit more precise estimates. But variability in earthquake events is not the only source of uncertainty; the probabilistic method is also hampered in areas where quakes are very infrequent or have poor surface expression, and where geophysical and geodetic data are sparse. Intraplate quakes, in particular, tend to have very long recur-

[49] A probabilistic forecasting model, for example, incorporates the regional stress field, rate of crustal deformation in the vicinity Of the fault, and strain accumulation with seismologic and geologic data.

[50] Estimates of earthquake potential are also used in deterministic assessments of seismic hazards (i.e., the calculation of strong ground motions for a specific earthquake scenario and site); these are frequently used in building design and the construction of seismically resistant structures.

rence times (e.g., thousands of years), and few have surface expression.

Thus earthquake prediction may hinge on interpreting certain warning signs rather than enhancing current models of the seismic cycle. As a first step, it is essential to verify whether or not such signs exist. Box 2-6 discusses research questions related to earthquake prediction.

Foretelling Earthquake Effects

In addition to determining earthquake potential, an equally important task for the earth science community is to give planners and engineers precise information on what earthquakes will actually do to the earth's surface that threatens the built environment. Earth science R&D with more immediate application to mitigation has historically been overshadowed by the basic research disciplines, but is now receiving increased emphasis (a breakdown of funding levels is given in appendix B). This applied research is of great importance for two reasons.

First, because earthquake effects on the earth's surface are complex, improving the seismic resistance of lifelines, buildings, and their contents requires detailed knowledge of the physical forces they will encounter. Second, the initial expenses of some mitigation measures are such that at-risk communities may have difficulty implementing them. The use of broad-brush, regionwide mitigation measures is often constrained by political and economic concerns (see chapter 4). Research that can identify locations of extreme danger and areas of relative safety can thus allow communities to target limited resources to where they will do most good.

This work includes the fields of strong-motion studies and seismic zonation (and its subset, microzonation).[51] Its objective is to examine—and quantify where possible—how seismic waves interact with particular aspects of local geology and geography to produce potentially damaging effects, including ground shaking, soil amplification, liquefaction, and tsunamis. The following discussion explains related studies and their applications in more detail.

General Ground Shaking

To design buildings and other structures that resist seismic damage, the engineering community requires quantitative estimates of the accelerations, velocities, and displacements that will occur in future earthquakes. Producing such estimates requires knowledge of:

- future earthquake magnitude;
- the location, orientation, and size of the likely earthquake fault;
- the attenuation characteristics of geologic material lying between the earthquake location and the area of concern (to determine how rapidly seismic waves decay with distance from the epicenter); and
- the general soil characteristics of the region.

This work is partly theoretical and partly empirical; it typically involves the correlation of laboratory predictions with data recovered from strong-motion seismometers in real-world earthquakes[52] (see box 2-7). Useful data can also be obtained by temporary regional-scale seismic networks deployed in an earthquake's aftermath to record the effects of aftershocks.

[51] *Strong-motion studies* focus on the shaking effects that seismic waves impose on the earth's surface, while *zonation* is a broader field that incorporates such indirect earthquake hazards as landslides and tsunamis, as well. *Microzonation* is hazard assessment on the scale of a town or city block.

[52] Strong-motion devices differ from traditional seismometers in that they can record the strong, violent ground motions from a nearby earthquake without failing or going off-scale (traditional observatory-grade seismometers are sensitive instruments designed to detect the faint tremors from distant seismic events and cannot handle strong shocks). Gathering strong-motion data has thus historically meant the deployment of specialized instruments for the task. However, recent technical developments have allowed some modern seismometers to function both as strong-motion instruments and as observatory devices, and they are increasingly used in many of the newest seismic networks.

BOX 2-6: Earthquake Prediction

To date, programs directed at predicting earthquakes have had mixed success, The central questions include: 1) are there specific physical conditions that Indicate the location, timing, and size of future earthquakes; 2) are current research programs adequately designed to capture and permit assessment of potential precursors?

- **Is there a recognizable pattern to earthquakes?**

Through statistical analysts of worldwide earthquake occurrences, one can estimate the frequency of different magnitude quakes across the globe. The monitoring of global seismicity also makes it clear that certain areas are much more prone to quakes than others—90 percent of the world's earthquakes occur on the boundaries of large tectonic plates

Along a single plate boundary, however, there can be considerable variability in the size and frequency of significant earthquakes. For example, parts of the San Andreas fault accommodate the relative motion of the North American and Pacific Plates without earthquakes (i.e., through aseismic slip); other sections of the fault have experienced several large or major quakes during recorded history. In general, intraplate earthquake sources and processes are even less well known Thus, a better understanding of the relationships among plate tectonics, regional stresses, and earthquake sources is needed.

- **Is an earthquake's size "known" at the time of its initiation?**

Scientists are making progress in understanding earthquake genesis and growth, although there IS not yet consensus on whether the eventual magnitude of the quake is random or somehow programmed into the surrounding rock, Recent observations of earthquake sources using advanced seismographic instruments, however, show that earthquakes Initiate with a distinctive seismic nucleation phase and that the size and duration of the nucleation phase appear to scale with the eventual size of the earthquake. ' These new and somewhat controversial results suggest that conditions favoring the growth of large, potentially destructive earthquakes are fundamentally different from those that lead to more common, smaller events, If so, careful geologic and geophysical monitoring might someday detect the conditions that signal the imminent risk of a large earthquake.

Local geology (and topography) may also have a role in whether larger, less frequent quakes (or smaller, more frequent ones) are to be expected on a fault [2]Advanced models of rupture propagation, additional geophysical data, and additional seismological data from newer broadband, high-dynamic range instruments will likely aid in understanding how surficial and subsurface fault characteristics affect rupture and maximum magnitude.

- **Does the state of stress that causes an earthquake to initiate and a fault to rupture betray itself through characteristic signals?**

The standard approach to developing a prediction capability hinges on the earth's providing recognizable signals of impending quakes. Ideally, much as we have come to associate certain symptoms with the onset of a cold, scientists could detect reliable Indicators of an earthquake's occurrence in advance of the event itself.

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1 W L Ellsworth and G C Beroza, "Seismic Evidence for an Earthquake Nucleation Phase, " Science, VOl 268, 1995, p 851

[2]Scientists look for the presence of rough patches in the fault (asperities) through analysis of seismograms, physical separation (e.g., step-overs) between fault segments, or other geologic barriers to the spread of the rupture zone

(continued)

BOX 2-6 (cont'd.): Earthquake Prediction

Theoretical and laboratory studies indicate there should be a preliminary phase prior to rupture. Potential earthquake precursors include: foreshocks (as material starts to fail under the extreme stress or strain), changes in the groundwater table (these occur when water-bearing pores in the rock start to deform under the stress) and other hydrologic or hydrothermal phenomena, deformation of the earth's surface, changes in the rock's electrical conductivity or magnetic properties, and changes in seismic wave properties through the area in question. In the past, such phenomena have been observed in the field, but not consistently.[3]

Broad efforts to Identify potential precursors are being pursued in China, Japan, and the former Soviet Union through extensive monitoring of seismicity, crustal deformation, and a variety of other phenomena. Chinese scientists were able to predict the 1975 M7.4 quake in Haicheng and the August 1976 M7.2 Songpan earthquake.[4] However, they were unable to predict the July 1976 Tangshan earthquake (M7.8), which killed hundreds of thousands. In Japan, public warning was achieved for the 1978 Izu-Oshima earthquake (M7).[5] Japan's monitoring and prediction program focuses primarily on the region surrounding Tokyo, which has the highest seismic risk. The Kobe locale, assigned a very low hazard, received little prediction attention.

It is important to note that Japan's monitoring program is directed at subduction zone earthquakes and may not be applicable to the strike-slip boundary on the U.S. West Coast.[6]

Earthquake Prediction in the United States

The first U.S. effort directed at earthquake prediction was located near the central California town of Parkfield, adjacent to the San Andreas fault. The Parkfield prediction experiment was begun in 1985 after analysis of previous earthquake occurrences on a particular fault section indicated that a repeat event would occur near the end of the decade.[7] The expected "characteristic earthquake" did not happen within the prediction window.

Further analysis showed that, while the successive repeat of similar (but not identical) quakes might be expected on individual fault sections, the amount of time between them may be highly variable Confidence in predictions based on estimations of recurrence intervals has decreased; scientists are more sanguine about the possibility of identifying one or more of the "red flags" described above.[8]

Today, the Parkfield experiment operates 21 instrument networks to record pre-earthquake phenomena (e.g. strain transients, electromagnetic signals); five of these networks are monitored in real time Ten additional networks are in place to record strong ground motion, co-seismic slip, and liquefaction [9]

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[3] Paul Silver, Department of Terrestrial Magnetism, Carnegie Institution, personal communication, Apr 5, 1994

[4] Cinna Lomnitz, *Fundamentals of Earthquake Prediction (New* York, NY: John Wiley & Sons, Inc., 1994), pp. 22, 29-30 Some argue that the Haicheng quake was easy to predict because there were many foreshocks the day before the main shock

[5] Evelyn Roeloffs and John Langbein, "The Earthquake Prediction Experiment at Parkfield, California, " AGU *Reviews of Geophysics,* vol. 32, No 3, August 1994, p 315

[6] The Japanese program has also been the subject of much criticism for its expense, lack of openness, and lack Of results. See, e g , Robert J Geller, "Shake-up for Earthquake Prediction, " *Nature, vol. 352, No. 6333,* July 25, 1991, pp. 275-276

[7] Parkfield has experienced moderate quakes six times since 1857. In 1985, on the basis of this sequence, the recurrence interval for M6 quakes near Parkfield was estimated to be about 22 years, and it was estimated with 95 percent confidence that another similar event would occur before 1993 Roeloffs and Langbein, see footnote 5, p. 315, citing W.H. Bakun and A G Lindh, "The Parkfield, California, Earthquake Prediction Experiment, " *Scier_rce,* vol. 229, 1985, pp. 619-624.

[8] Silver, see footnote 3

[9] Roeloffs and Langbein, see footnote 5.

BOX 2-6 (cont'd.): Earthquake Predic

Assessing Prediction Feasibility

For prediction to be feasible, however, scientists must be able not only to recognize the red flags, but also to determine the relationship between these precursors and succeeding earthquakes. In addition, the red flags must have some predictive power; that is, there must be a sound correlation between their occurrence and the subsequent occurrence of significant earthquakes.[10]

According to some scientists, while the current monitoring program at Parkfield may yield useful data for that specific spot, it is not comprehensive enough to verify whether or not prediction is feasible. Instead, they advocate a more extensive program to monitor multiple types of potential precursors throughout the San Andreas fault zone. New observation techniques (e. g., space-based geodetic surveys and Imagery of crustal deformation) could provide the necessary broad coverage and complement in situ monitoring and fault studies.

Given the complexity of such an undertaking, as well as the relative infrequency of damaging U.S. earthquakes, results from this effort might not be expected for another few decades.

10 silver, see footnote 3

SOURCE Off Ice of Technology Assessment, 1995.

Early Warning

Advances in seismometers and telecommunications, along with automated analysis of earthquake events, may soon permit early warning of seismic waves capable of producing strong ground motion. Because electronically transmitted information travels at a much faster rate than seismic waves travel through the earth, real-time warning of severe shaking approaching a populated area or lifelines will be possible given monitoring systems that can automatically determine a quake's location and magnitude and estimate the strong-motion characteristics within a few seconds.[53] Early warning systems hold the potential for automated response during an earthquake and more rapid, effective response after the shaking stops.

Amplification Effects

Engineers and planners within specific communities also must be aware of the possibility of localized, unusually high amounts of ground shaking. These "hot spots" can result from simple soil amplification, in which the presence of soft soils and sediments at the earth's surface significantly increases the amplitude of passing seismic waves (see figure 2-8).

The collection of ground motion records from recent large California quakes and their aftershocks, as well as from recent events in Mexico and Japan, has aided in understanding site effects in these areas.[54] However, records for other areas of the United States are very limited. In addition, significant geotechnical modeling is still needed

53 Post-earthquake notification systems have been operating in southern California since 1991 and in northern California since 1993. System operators expect to achieve early warning capabilities within a few years.

54 Stephen Hartzell, U.S. Geological Survey, Earthquake and Landslide Hazards Branch, personal communication, Oct. 20, 1994.

BOX 2-7: Strong Motion Record

Beside the seismometer, another essential tool for defining the impact of a quake is the strong-motion accelerograph, typically housed in or near buildings, dams, and other critical engineered structures. *Strong motion* is used to mean ground motions that are sufficiently large to cause damage to structures; a strong-motion accelerograph is intended to record these large motions without signal saturation. The data generally are used for engineering purposes and, until recently, the instruments were usually triggered only by events of a minimum magnitude (e.g., M4.5 for local events or higher for distant quakes).

The development of regional seismographic networks began in the 1960s in response to the need to learn more about the distribution of seismicity with areas of recognized earthquake hazards. Because the primary objective of their implementation was the construction of a catalog of earthquake activity with high spatial resolution, the seismometers were adjusted to record smaller, more numerous earthquakes. This, combined with the use of analog data telemetry to meet high sample rate requirements and an emphasis on high-frequency ground motions, limited the effective dynamic range of the monitoring networks. As a result, the recording of strong ground motions was largely sacrificed.

Now, digital strong-motion instruments are being Integrated into seismic observatories that record both weak and strong ground motions.

The majority of strong-motion networks are located in the western states; with these instruments, scientists and earthquake engineers have obtained a fairly extensive strong-motion data set for the southwestern United States. Few records exist for other parts of the country and, more importantly, there are no near-field records from damaging quakes in U.S. urban centers. This means that scientists and engineers still lack empirical knowledge of the effects of earthquakes that occur directly beneath densely populated areas. '

[1] The 1994 Northridge quake occurred in a largely suburban area, and its largest motions were focused toward less populated areas The ground motions in downtown Los Angeles produced by a quake on the buried Elysian Park thrust fault, for example, would likely be much larger than those experienced above the source of the Northridge quake Likewise, the 1989 Loma Prieta quake occurred several miles from heavily populated centers in the San Francisco Bay area.

SOURCE: Office of Technology Assessment, 1995, based on Thomas H. Heaton et al , "National Seismic System Science Plan," U S Geological Survey Circular 1031 (Washington, DC: U.S. Government Printing Office, 1989)

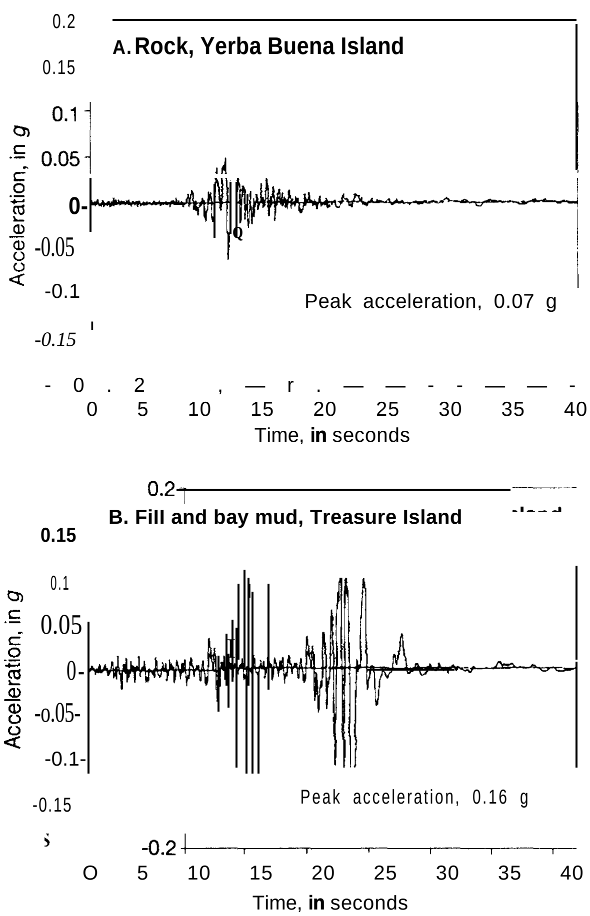
to address several facets of site response, including soil properties, stratigraphy, and ground motions that occur in the immediate vicinity of a fault.[55]

Other factors in unusual ground shaking are: 1) basin effects, in which sedimentary basins (large, bowl-shaped deposits of river or lake-borne sands, soils, and clays, on which most of the country's urban centers are built) trap, accumulate, and amplify passing seismic waves (see box 2-8); and 2) ridge effects, in which topographic features such as hills and valleys can focus seismic waves together in the manner of a lens.[56]

[55] Examples are: nonlinear response of soft, weak soils; deep basin response; deep cohesive sites and shallow, stiff soils; two- and three-dimensional topographic and stratigraphic effects; and near-field motions and spatial incoherence. Ray Seed, Earthquake Engineering Research Center, University of California, Berkeley, personal communication, Nov. 3, 1994.

[56] Amplification and basin effects were largely responsible for the unusual amount of devastation wrought in the Mexico City earthquake of 1985, as well as for damage to the Marina District of San Francisco in the 1989 Loma Prieta quake. Ridge effects in the Loma Prieta event are thought to have been responsible for vertical accelerations in excess of 1 g in certain severely damaged neighborhoods.

FIGURE 2-8: Effects of Local Geological Conditions on Ground Motion



NOTE" Recorded horizontal ground motion (east-west direction) from the 1989 M7.1 Loma Prieta earthquake,

SOURCE: U.S. Geological Survey, 1995

Predicting amplification effects is in theory straightforward, since the scientific principles involved are well understood. However, accurate estimates require detailed knowledge of local geology (which typically demands a special effort), as well as specific predictions of the future earthquake's source characteristics (i.e., fault rupture characteristics and the consequent nature of the initial seismic waves).

Ground *Failure*

Combining knowledge of the potential for strong shaking and of local geology and soil conditions yields an improved capability to identify the potential for liquefaction, landslides, and other forms of ground failure. When water-saturated soils and sediments turn into a quicksand-like slurry during extended shaking, they lose the ability to bear loads, thus causing even seismically resistant buildings and structures to fail at the foundation. Lateral spreading or permanent ground displacement also can cause great damage to buried utilities or port facilities. These phenomena are of particular concern to planners and local policymakers, because sites prone to such failure may require extraordinary preventive measures or relegation to less vulnerable forms of land use.

Geographical Information System (GIS) tools have been increasingly utilized in assessing these hazards and in analyzing related risks to special facilities or structures. Primarily a research tool today with respect to earthquake hazards, GIS-based maps can be readily converted to a larger educational-or policy—tool as well.[57]

In addition, systems have been proposed for both northern and southern California that will incorporate knowledge of a quake's location, size, and faulting mechanism into preexisting databases on shallow soil structure and the built environment.[58] Their objective is to quickly map the zones with most severe ground motion, which will indicate where emergency managers should look for the most damage and should direct response teams.

Tsunamis and Seiches

In addition to knowledge of the hazardous effects described above, coastal communities also require warnings of the possibility of tsunamis and

57 Arthur C. Tarr, U.S. Geological Survey, Earthquake and Landslide Hazards Branch, personal communication, Oct. 21, 1994.

58 Barbara Romanowicz, Seismic Research Center, University of California, Berkeley, personal communication, Nov. 3, 1994.

BOX 2-8: Basin Effects

Most of the large urban areas in the United States have developed on sediment-filled basins, which can strongly modify the ground motion from an earthquake.[1] It is believed that the shape and material properties of a sedimentary basin allow it to focus and collect seismic waves.[2] The result is large-amplitude surface waves that reverberate long after the rupture itself has ceased. Until recently, however, models of the earth's structure and wave propagation could not represent these conditions.

Under NEHRP, the U.S. Geological Survey is applying new three-dimensional modeling techniques to the case of complex propagation effects for the San Bernardino Valley east of Los Angeles, through which the San Andreas fault passes. The simulated effects include high ground velocities in localized portions of the basin, which could pose significant risk to structures with natural periods of one second or longer (e.g., buildings of 10 or more stories, some highway overpasses, and elevated pipelines).[3] Similar studies are under way for the San Francisco Bay area and Washington State's Puget Sound region.

[1] Stephen Hartzell, U.S. Geological Survey, Earthquake and Landslide Hazards branch, personal communication, Oct 20, 1994

[2] Thomas H, Heaton and Stephen H. Hartzell, "Earthquake Ground Motions," *Annual Review of Earth Plantary Science,* vol. **16, 1988,** p. 127, citing J A. Rial, "Caustics and Focusing Produced by Sedimentary Basins, Applications of Catastrophe Theory to Earthquake Seismology," *Geophysical Journal of the Royal Astronomical Society, vol.* 79, 1984, pp 923-38.

[3] Arthur Frankel, "Three-Dimensional Simulations of Ground Motions in the San Bernardino Valley, California, for Hypothetical Earthquakes on the San Andreas Fault," *Bulletin of the Seismological Society of America, vol. 83, No.* 4, August 1993, p 1021

SOURCE. Off Ice of Technology Assessment, 1995.

seiches. Research into these hazards-which seeks to understand why they are generated by some earthquakes and not others—blends the scientific fields of seismology and oceanography. Such research has a considerable international component (although tsunamis and seiches do take place in the United States, considerably more experience has been gained by Japan and other countries of the far Pacific Rim) and is frustrated by the unusual physical characteristics of the phenomena. Tsunamis, for example, exist in the open ocean as extremely fast, extremely broad, but extremely low waves that can pass beneath ships completely undetected.[59] Given these characteristics, specialized tsunami detection equipment is necessary both for research and for establishing early warning systems for coastal communities.[60] The National Oceanic and Atmospheric Administration operates the U.S. tsunami warning system.

A common thread in all these applied research efforts is that they require collaboration between specialists in the traditional seismic research community and practitioners in other earth science and engineering disciplines. Moreover, the work cannot be accomplished purely through theory or lab-

[59] The danger of tsunamis is that, although extremely low in the open ocean (only inches high), they are long enough to contain a considerable amount of water (tsunami waves can stretch a hundred miles crest to crest), and fast enough to propel that water far inland. Speeds of hundreds of miles per hour are common. In a damaging tsunami strike, the incoming wave slows down as it approaches land. As it slows, the back of the wave catches up with the front, the wave height builds to many tens of feet, and the wave ultimately washes ashore as a huge surge of water.

[60] Because tsunami waves are so broad and low, their detection in the open ocean requires devices akin to tide gauges (i.e., instruments that can detect the passage of an open-ocean tsunami amid normal wind-driven waves).

oratory experiments; gathering detailed geologic information on each region or locality of interest requires a concerted effort.[61]

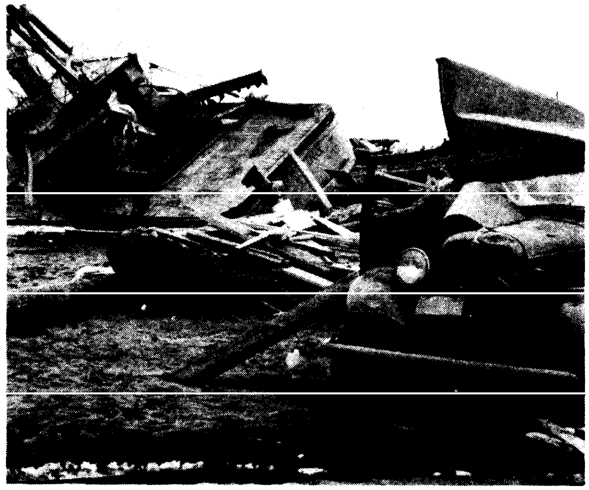
For example, the U.S. Geological Survey prepares maps of seismic hazards on national and regional scales, using a variety of data sources and modeling techniques (see figure 2-9). Maps of expected ground shaking are converted by the engineering community into design maps that reflect current engineering analyses; they form the foundation for model seismic codes. In addition, regional hazard maps support state and local land-use planning efforts, and can pinpoint areas where further study is warranted.

SUMMARY AND KEY FINDINGS

Earthquake hazards vary widely across the United States. The most active seismic regions in the United States are Alaska and California; their high seismicity stems from proximity to the boundaries between shifting segments of the earth's crust. However, few parts of the United States are immune to quake hazards. Significant earthquakes have occurred in the Pacific Northwest, in the central United States, and along the east coast.

Earth science research, in which NEHRP has played a key role, has advanced significantly our understanding of U.S. seismic hazards. It is now possible to estimate the likelihood of future earthquakes for a few areas (the San Francisco Bay and greater Los Angeles areas, where many years of study have helped to reduce uncertainties; Utah's Wasatch fault zone; and the New Madrid Seismic Zone). In the near future, scientists maybe able to do the same for other regions of the United States.

The importance of local soil conditions and other factors that influence the type and degree of damage an earthquake can cause (e.g., soil amplification and landslides) are now recognized and better understood. It is now possible to produce detailed maps showing specific hazards resulting



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Valdez, Alaska, waterfront after tsunami caused by 1964 Good Friday earthquake.

from local soils, and provide more detailed and accurate expected ground motion information for use in building design and model code development. Within a few years, researchers expect to be able to provide real-time warnings of approaching strong shaking.

Despite the numerous advances, however, significant uncertainties and knowledge gaps remain. Scientists are far from able to determine the specific time, location, and magnitude of future earthquakes. Among the key unknowns are questions about the constitutive properties of faults, the interactions of different fault systems, and the mechanisms of rupture. Additionally, in many areas of the country, the location of faults capable of producing damaging earthquakes is still not known, nor is the likelihood of these earthquakes or the extent of their hazardous effects.

There are many societally useful directions for future earthquake-related earth science research. A key issue is how to strike the appropriate balance between types of research efforts and among different geographical areas, given both financial and time constraints. As with many research-in-

[61] The effort to gather such information (i.e., geologic and geophysical mapping) is often carried out for other purposes by USGS and by private concerns such as the petroleum and mineral exploration industries. The oil and mineral industries are very competitive; companies are often understandably hesitant to make data gathered at considerable expense available to competitors.

FIGURE 2-9: Seismic Hazard Map Development Process

Seismic hazard maps
National and regional

→ Design value maps for building codes

Quantify the rates of occurrence, magnitudes and probable locations

- Analyze historical seismicity
- In the western United States, determine recurrence rates and magnitudes of large prehistoric earthquakes on faults.
- In the central and eastern United States, study pre-historic quakes with paleoliquefaction
- Evaluate geologic structures associated with seismicity.
- Estimate maximum magnitudes from geologic structures.

Quantify the ground motions that will be produced by these earthquakes

- Determine the ground motions as a function of magnitude and distance.
- Analyze seismograms to assess source, site, and path effects.
- Assess regional variations in ground motions (e.g., between western and central or eastern United States).
- Map geology to determine site amplification.

SOURCE U S. Geological Survey, 1995.

tensive efforts, it is difficult to quantitatively assess the value of different activities; determining the balance between applied research directed at near-term results and longer term research is a political, not merely a scientific, challenge. Even within the earth science community, tension exists over how to divide resources between expanding the fundamental understanding of quake phenomena and concentrating on mapping hazardous site conditions in areas where damaging seismicity has already occurred.

Decisions on how to allocate earth science research funds should be made in the context of the goals of the earthquake program (discussed in chapter 1). However, several research areas clearly deserve attention:

- **Microzonation.** To better assess the overall risk posed to inhabitants and the built environment, analysis of the potential for strong shaking or ground failure is needed on finer scales. This requires not only the application of improved models of earthquake potential and expected shaking, but detailed mapping of near-surface geology and site conditions. Such microzonation studies have been completed in only a few areas of the United States. Thus, we have an incomplete picture of the probability of significant hazards near populated areas or critical facilities for all but the most intensely studied zones (i.e., the San Francisco Bay area and greater Los Angeles region). Additional emphasis should be placed on microzonation in urban areas and around critical facilities where long-duration, strong shaking is expected.

- **Earthquake potential.** New technologies and practices have enabled significant additions to the body of knowledge required to understand the potential for earthquakes in different areas. Paleoseismology permits more reliable estimates of the magnitude and dates of prior earthquakes, especially in areas where damaging earthquakes have very long recurrence times. This information is essential to gauging the likelihood of future damaging events within a decades-long time frame.
- Satellite-based geodetic techniques have revolutionized the observation and modeling of crustal deformation, which contributes to assessments of crustal stress and strain. This information supports long-term forecasts of earthquake potential. In addition, further enhancements to the scope and accuracy of these techniques could provide the foundation for new imaging methods that, akin to weather forecasting, facilitate reliable earthquake prediction.
- **Geographic focus.** Because of its frequent damaging earthquakes, California is the test bed for the development of many current theories and techniques. However, some of these may not be readily adapted to the Pacific Northwest or to the central and eastern United States. Additional research and data collection specific to these latter areas should be considered to determine what distinguishes the nature of the hazards and to support the application of existing tools.
- **International focus.** Fortunately for those who experience damaging earthquakes, the events are few and far between. This leaves the scientific community at a disadvantage, however, with respect to opportunities to incorporate data into the seismic record and evaluate theoretical models of seismic phenomena. Field investigations and analyses of data from earthquakes that occur outside our borders are crucial to understanding similar U.S. seismic hazards (e.g., subduction and intraplate quakes that have occurred here rarely).
- **Knowledge transfer.** It is essential to maintain efforts to make new knowledge and tools readily available to potential users. In recent years, the earth science research community and NEHRP research agencies have put increased emphasis on knowledge transfer to professionals and the general public. These efforts, although difficult to evaluate, are crucial to ensuring that research results help to accelerate the pace of earthquake mitigation throughout the country.